REPORT No. 655

THE KNOCKING CHARACTERISTICS OF FUELS IN RELATION TO MAXIMUM PERMISSIBLE PERFORMANCE OF AIRCRAFT ENGINES

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SUMMARY

An analysis is presented of the relationship of various engine factors to knock or preignition in an aircraft engine. From this analysis and from the available experimental data, a method of evaluating the knocking characteristics of the fuel in an aircraft-engine cylinder is suggested. Because the method is based on the physical factors controlling knock, the knocking-characteristic curve for each fuel expresses the relative maximum permissible engine performance obtainable from the fuel. Curves are presented showing the manner in which the knocking-characteristic curve can be used to predict the relationship between compression ratio and maximum permissible indicated mean effective pressure, minimum permissible specific fuel consumption, and maximum permissible peak pressure for any one fuel. Additional curves show that the knocking-characteristic curves permit a rational choice to be made between two or more fuels or permit the fuel to be selected that most satisfactorily meets the given engine requirements. The suggested method of determining the knocking characteristics is compared with the octane-number scale. Throughout the discussion, the susceptibility of the fuels to the temperature conditions within the engine is emphasized.

INTRODUCTION

The knocking characteristic of a fuel is the most important factor in determining the maximum permissible performance obtainable from that fuel in a spark-ignition engine. For this reason, extensive researches have been conducted in an effort to rate fuels according to their knocking characteristics in aircraft engines. Most of these investigations have been conducted with the idea of determining a simple method by which the knocking characteristics of various fuels can be compared on an empirical basis. In order to determine the maximum permissible engine performance obtainable from any one fuel, the problem must be attacked from a somewhat different angle. The question becomes one of defining basic relationships between the different engine variables and the limiting engine performance. The characteristics of the individual engine become important as well as the characteristics of the fuel. If the basic relationships can be determined, it should be possible to predict the maximum permissible engine performance under numerous engine operating conditions from tests conducted under a few operating conditions.

The problem resolves itself, therefore, into two parts: First, a correlation of the effect of the various engine factors on the knocking characteristics of the fuel or, since the knocking characteristic of the fuel is the primary independent variable, the correlation between the knocking characteristics of the fuel and the permissible combinations of the different engine variables; and, second, a determination of the maximum permissible engine performance based upon this correlation.

A correlation between the different variables having once been obtained, the results can be expressed in the form of one or more curves depending on the number of independent variables. Such curves have already been presented in reference 1 and have been suggested as a method of rating fuels. Serruys (reference 2) has shown data that correlate maximum permissible peak pressure, compression ratio, and power output.

In the present report, the data presented in reference 1 are extended and analyses are made of these data and of the results of other investigators so that a correlation of the various engine factors can be obtained. From this analysis it is shown that a single curve obtained from the variation of a few conditions represents the knocking characteristics of the fuel in an engine over a wide variety of conditions.

In the second part of the report it is shown that, from the knocking characteristics of the fuels obtained on various engines, estimates can be made of the effect of compression ratio, inlet-air temperature, and inlet-air pressure on the maximum permissible indicated mean effective pressure, minimum permissible specific fuel consumption, and maximum permissible peak pressure.

A third section is included in which the knocking characteristics are compared with the octane numbers of the fuels investigated.

I—DETERMINATION OF KNOCKING CHARACTERISTICS

The phenomena that limit the severity of engine conditions to which a fuel can be subjected are knock and preignition. Knock, or detonation, is defined as a combustion phenomenon that results in an abnormal and uncontrollable rate of pressure rise near the end of combustion, which takes place with sufficient rapidity to set up waves within the gas that travel at velocities equal to or greater than that of sound in the gaseous medium. Preignition is defined as ignition of the charge by some source other than the ignition spark and prior to the ignition spark.

KNOCK

Knock in spark-ignition engines, according to the most generally accepted concept, is the result of the almost simultaneous burning of the end gases in the combustion chamber. This burning is of sufficient rapidity to cause a sudden increase in the pressure in part of the combustion chamber. The pressure increase takes place at a rate more rapid than the rate at which the pressure is transmitted through the gas. Therefore a system of pressure waves is set up within the chamber. These gas vibrations strike the combustion-chamber wall and induce vibrations in the engine structure, which give rise to the metallic knock.

More recent data obtained at this laboratory (reference 3) have led to the conclusion that knock may not necessarily be the auto-ignition of the end gas, because knock has been observed after the combustion front has apparently traversed the end gas. Regardless of the nature of knock, the effect on the pressures within the cylinder is the same—a sudden increase in the local pressures, and, with heavy knock, a sudden increase also in the mean pressure throughout the chamber. Knock, if sufficiently severe, is accompanied by an eventual loss in power, possible preignition, and, if continued, results in overheating of the engine and consequent engine failure.

PREIGNITION

Preignition is generally surface ignition at some hot spot in the combustion chamber. The effect of preignition is the same as that obtained by advancing the spark timing, that is, combustion starts too early in the cycle. As a result, there is loss of power and overheating of the engine (unless the spark has been retarded to a value less than that for optimum power). The early start of combustion may also be accompanied by knock although this is not necessarily the case. Some fuels, such as benzene, are prone to preignite although in the pure state they do not knock. The combustion started by preignition is not essentially different from that started by the electric spark at the spark plug. The difficulties caused by preignition result from a lack of control of the time at which ignition starts.

In the present report, most of the data discussed relate to knock and not to preignition. The analysis of the method of estimating maximum permissible engine performance will be based on knocking fuels and not on preigniting fuels.

ENGINE FACTORS INVOLVED

Knock and preignition are phenomena of combustion; they must therefore be controlled by the physical state of the gases within the combustion chamber as well as by the chemical composition of the gases. The conditions that control the state and the composition of the gases within the combustion chamber are:

(*a*) Chemical composition of the fuel.
(*b*) Fuel-air ratio.
(*c*) Exhaust-gas dilution.
(*d*) Humidity.
(*e*) Compression ratio.
(*f*) Inlet-air temperature.
(*g*) Inlet-air pressure or density.
(*h*) Wall temperature of combustion chamber and cylinder.
(*i*) Spark advance.
(*j*) Engine speed.
(*k*) Engine dimensions.
(*l*) Combustion-chamber form.

All these factors affect, either directly or indirectly, the chemical and the physical properties of the gases within the combustion chamber at the time knock or preignition takes place. In the determination of knocking or preigniting characteristics of fuels, the relationship that is to be derived is the effect of the chemical composition of the fuel or the effect of different fuels on the values of the other 11 factors that result in knock or preignition.

TEMPERATURE-DENSITY RELATIONSHIP

It seems reasonable to assume that the temperature and the density of the combustion gas just prior to knock are the physical properties of the combustion gas which determine whether or not the fuel knocks. If the assumption is accepted that the two physical properties controlling knock are the gas temperature and the gas density, it can be said that, for each gas density, there is a corresponding gas temperature at which knock will occur. It follows that, if this contention is true, the knocking characteristics of a fuel in any engine can be determined from the relationship between the gas temperature and density which results in knock. A second and equally important contention that must necessarily follow is the impossibility of adequately expressing the knocking characteristics of a fuel by determining one and only one combination of temperature and density at which knock occurs.

Since preignition is generally the result of a hot spot in the combustion chamber, it is reasonable to assume that the secondary ignition characteristics of fuel can best be obtained by determining the relationship between the hot-spot temperature and the temperature and the density of the combustion gases which result in this secondary ignition. It is probable that the temperature of the hot spot in this case is more important than the temperature of the gases. But, again, the fuels must not be evaluated at any one set of engine conditions but over a sufficient variety of engine conditions to permit a temperature-density relationship for preignition to be determined.

Determination of temperature-density relationship.—The immediate cause of knock is the gas density and temperature in the knocking region of the combustion chamber the instant before knock occurs. If the explosion pressure just previous to knock can be measured, the temperature-density relationship can be obtained from a method similar to that presented by Serruys in reference 2. Inasmuch as the knock apparently occurs in the last part of the charge to burn (whether it is previous to or after the propagation of the normal flame through this region does not affect the analysis), the temperature and the density of this gas can be used as the criterion for determining the conditions that cause knock. This portion of the charge is compressed by the previously burning mixture as well as by the piston during the compression stroke. The actual value of these ratios need not be known to estimate the temperature and the density, provided that the peak combustion pressure preceding knock is known.

From the conventional thermodynamic equations, the density of this end gas previous to its combustion, as the intensity of the knock approaches zero, can be expressed as:

$$K\rho_3=\frac{P_1}{T_1}\left(\frac{P_3}{P_1}\right)^{\frac{1}{\gamma}} \tag{1}$$

and the temperature in the knocking zone as:

$$T_3=T_1\left(\frac{P_3}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \tag{2}$$

in which ρ_3 is the gas density in the knocking zone immediately preceding knock.

P_1, the inlet-air pressure.

T_1, the inlet-air temperature.

P_3, the pressure immediately preceding knock.

γ, the adiabatic coefficient.

T_3, the temperature in the knocking zone immediately preceding knock.

K, a constant.

It will be noticed that these expressions are the same as those given in reference 2 except that the density is used in place of the pressure.

In accordance with expressions (1) and (2), tests can be run with an engine at combinations of compression ratio, spark advance, inlet-air temperature, and inlet-air pressure that cause knock. From these results, equations (1) and (2) can be evaluated and a curve constructed from the resulting data. The equations involve neither the compression ratio of the engine nor the spark advance.

In general, it is not easy to make an accurate measurement of the peak pressures in an engine; therefore, the problem of correlating the effects of the different engine variables will be simplified if some other temperature and density in the cycle can be used. When the other factors are maintained constant, for optimum spark advance, the gas temperature and density in the knocking zone can be expressed in terms of the inlet-air pressure, the inlet-air temperature, and the compression ratio in the following manner: Equation (1) can be expressed as

$$K\rho_3=\frac{P_1}{T_1}\left(\frac{P_3}{P_2}\times\frac{P_2}{P_1}\right)^{\frac{1}{\gamma}}$$

If P_2 is the compression pressure, T_2 the absolute compression temperature, and T_3' the mean absolute temperature throughout the combustion chamber immediately preceding knock, the density ρ_3 can be expressed by:

$$K\rho_3=\frac{P_1}{T_1}\left(\frac{T_3'}{T_2}\right)^{\frac{1}{\gamma}}\left(\frac{P_2}{P_1}\right)^{\frac{1}{\gamma}}$$

But

$$T_3'=T_2+\frac{H}{c_v}=T_1R^{\gamma-1}+\frac{H}{c_v}$$

and

$$\left(\frac{P_2}{P_1}\right)^{\frac{1}{\gamma}}=R$$

in which H is the heat content per pound of mixture; c_v, the specific heat of the mixture at constant volume; and R, the compression ratio of the engine. Therefore

$$K\rho_3=\frac{RP_1}{T_1}\left(1+\frac{H}{c_vT_1R^{\gamma-1}}\right)^{\frac{1}{\gamma}} \tag{1a}$$

In expression (1a), RP_1/T_1 represents the density of the gases at top center, and the expression $(1+H/c_vT_1R^{\gamma-1})^{\frac{1}{\gamma}}$ represents the further compression of the gases in the end zone during the combustion period. By a similar analogy, it can be shown that

$$T_3=T_1R^{\gamma-1}\left(1+\frac{H}{c_vT_1R^{\gamma-1}}\right)^{\frac{\gamma-1}{\gamma}} \tag{2a}$$

In expression (2a), $T_1R^{\gamma-1}$ represents the compression temperature, and the expression $(1+H/c_vT_1R^{\gamma-1})^{\frac{\gamma-1}{\gamma}}$ represents the temperature increase in the end gas caused by the compression in this zone during the combustion.

In the evaluation of expressions (1a) and (2a), c_v is estimated to be 0.25 B. t. u. per pound per °F., γ to be 1.29, and H to be 1,160 B. t. u. per pound of mixture.

TABLE I

ESTIMATED TEMPERATURES OF END GAS T_3 FOR VARIOUS COMPRESSION RATIOS AND INLET-AIR TEMPERATURES

Compression ratio	Inlet-air temperature (° F.)			
	120	160	200	240
	T_3 (° F.)			
6	1,440	1,520	1,600	1,680
8	1,540	1,620	1,700	1,780
10	1,630	1,720	1,810	1,900
12	1,700	1,790	1,880	1,970

The values of T_3 for a series of compression ratios and inlet-air temperatures are given in table I. The table shows that, whereas an increase in compression ratio of from 6 to 8 increases the end-gas temperature 100° F., an increase in inlet temperature of from 120° F. to to 240° F. at the lower ratio increases the end-gas temperature 240° F. It can be concluded that, if temperature alone is considered, an increase in compression ratio in the normal operating range should not have any great effect on the fuel requirements of the engine. Any effect of increasing the compression ratio must therefore lie mainly in the increase of the gas density at top center.

In the determination of the knocking characteristics of fuels in an engine, it will be necessary to determine the temperature-density relationship for knocking combustion over a sufficient range of engine conditions to establish a definite curve. If the assumption is made for the moment that this curve (over the operating range) is a straight line, the results for two fuels of different chemical properties may appear as shown in figure 1. In this case, fuel A is superior to fuel B at low gas temperatures but fuel B is the better at high temperatures; fuel A is more susceptible to temperature variations than fuel B.

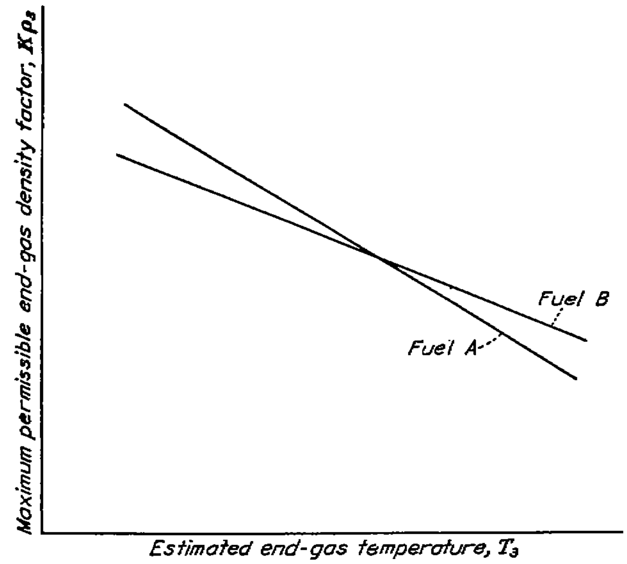

FIGURE 1.

The foregoing relationship can be established by keeping the compression ratio constant and varying the inlet-air temperature and pressure; by keeping the inlet-air pressure constant and varying the compression ratio and the inlet-air temperature; or, as will later be shown, by varying the engine-coolant or the jacket temperature instead of the air temperature.

Experimental check of temperature-density relationship.—Recent tests completed by the N. A. C. A. (reference 1) show the maximum permissible inlet-air pressure without knock for a series of compression ratios and inlet-air temperatures, using fuels made by blending commercial iso-octane (2, 2, 4—trimethylpentane) with a reference fuel of low knock rating. The commercial iso-octane was similar to the C. F. R. S-1 reference fuel and the fuel with low knock rating was similar to the C. F. R. M-1 reference fuel. The blends tested consisted of 85, 90, 95, and 100 percent of the iso-octane fuel and are so designated. In addition, the iso-octane was tested with 1.0 ml per gallon of tetraethyl lead.

TABLE II

EFFECT OF INLET-AIR TEMPERATURE ON MAXIMUM PERMISSIBLE INLET-AIR PRESSURE AT DIFFERENT COMPRESSION RATIOS

[Engine speed, 2,500 r. p. m.; coolant temperature, 250° F.; fuel-air ratio, 0.081; flat-disk combustion chamber]

Knock	Fuel	Inlet-air temperature, (° F.)	Compression ratio			
			6.50	7.25	8.00	8.75
			Inlet-air pressure (in. Hg abs.)			
Audible	85 percent iso-octane	120	32.5	--------	--------	------
		160	32.5	--------	--------	------
		200	32.5	--------	--------	------
		240	32.5	--------	--------	------
		280	--------	--------	--------	------
Do	90 percent iso-octane	120	35.0	32.5	--------	------
		160	35.0	32.5	--------	------
		200	32.5	--------	--------	------
		240	32.5	--------	--------	------
		280	32.0	--------	--------	------
Do	95 percent iso-octane	120	37.5	35.0	30.0	------
		160	37.5	35.0	--------	------
		200	35.0	32.5	--------	------
		240	32.5	--------	--------	------
		280	30.0	--------	--------	------
Do	Iso-octane	120	40.0	37.5	32.5	30.0
		160	40.0	32.5	32.5	30.0
		200	35.0	32.5	30.0	------
		240	35.0	32.5	--------	------
		280	30.0	30.0	--------	------
Do	Iso-octane + 1.0 ml tetraethyl lead.	120	([1])	([1])	37.5	32.5
		160	([1])	([1])	35.0	32.5
		200	([1])	([1])	32.5	30.0
		240	([1])	([1])	30.0	------
Improved cooling in center of cylinder head						
Audible	85 percent iso-octane	120	34.4	29.5	--------	------
		160	33.1	--------	--------	------
		200	32.1	--------	--------	------
		240	29.9	--------	--------	------
		280	29.7	--------	--------	------
Do	Iso-octane	120	40.7	35.8	34.2	31.4
		160	41.6	35.6	32.4	------
		200	39.8	33.2	29.4	------
		240	36.6	30.9	--------	------
		280	33.0	--------	--------	------
Incipient	do	120	37.6	30.7	29.2	27.1
		160	36.7	30.9	27.9	------
		200	35.6	29.4	--------	------
		240	33.7	29.5	--------	------
		280	30.2	--------	--------	------
Do	Iso-octane + 1.0 ml tetraethyl lead.	120	--------	48.5	43.9	41.8
		160	--------	48.2	45.6	41.2
		200	--------	46.2	39.3	33.1
		240	--------	42.9	34.7	32.5
		280	--------	40.6	32.7	30.3

[1] Maximum inlet-air pressure limited by preignition or afterignition.

Tables II, III, and IV show a summary of the results presented in reference 1 and of results subsequently obtained with the test engine. The test engine was operated at 2,500 and 2,200 r. p. m. and was cooled with ethylene glycol maintained at a temperature of 250° F. The engine dimensions are 5 by 5¾ inches. One flat-disk and one pent-roof combustion chamber were tested. The piston used with the pent-roof chamber had recesses cut in the top to prevent its contacting the valves at the high compression ratios. In the first series of

TABLE III

EFFECT OF INLET-AIR TEMPERATURE ON MAXIMUM PERMISSIBLE INLET-AIR PRESSURE AT DIFFERENT COMPRESSION RATIOS

[Engine speed, 2,200 r. p. m.; coolant temperature, 250° F.; fuel-air ratio for best power; knock, incipient; pent-roof combustion chamber; fuel, iso-octane]

Inlet-air temperature (° F.)	Compression ratio		
	6.50	7.25	8.00
	Inlet-air pressure (in. Hg absolute)		
120	40.2	36.1	33.3
160	40.0	36.6	32.1
200	37.2	----------	32.6
240	35.2	33.5	30.0
280	34.2	31.2	--------

TABLE IV

EFFECT OF INLET-AIR TEMPERATURE ON MAXIMUM PERMISSIBLE INLET-AIR PRESSURE AT DIFFERENT COMPRESSION RATIOS

[Engine speed, 2,500 r. p. m.; coolant temperature, 250° F.; fuel-air ratio, 0.078; knock, incipient; pent-roof combustion chamber]

Fuel	Inlet-air temperature (°F.)	Compression ratio		
		6.50	7.25	8.00
		Inlet-air pressure (in. Hg absolute)		
85 percent iso-octane	120	32.7	29.2	--------
	160	32.0	--------	--------
	220	31.1	--------	--------
	240	30.7	--------	--------
	290	30.3	--------	--------
90 percent iso-octane	120	34.6	31.6	--------
	160	34.1	31.1	--------
	210	33.3	30.2	--------
	250	32.5	--------	--------
	300	31.5	--------	--------
95 percent iso-octane	120	37.9	34.2	32.2
	160	37.8	33.8	31.0
	210	36.4	33.1	31.1
	260	35.6	31.2	--------
	300	33.2	30.8	--------
Iso-octane	120	43.1	38.3	34.7
	170	42.7	37.7	35.1
	210	41.2	37.1	34.8
	250	39.8	34.9	32.9
	300	37.4	33.7	31.6
Iso-octane+1.0 ml tetraethyl lead	210	55.1	49.5	44.3
	250	53.5	47.0	40.7
	300	48.9	44.3	39.1

tests with the flat-disk chamber and the leaded fuel, preignition or afterignition was observed at the two lower compression ratios. Afterignition consisted of firing after the ignition switch had been turned off. These data are not listed because in these tests the limit imposed by knock was desired. Improved cooling to the center of the cylinder head removed the hot spot that caused this secondary ignition, and the second set of data so indicated was recorded. It will be noticed that, for the 85- and 100-percent iso-octane, there was no appreciable change in the maximum permissible inlet-air pressure when the cooling of the cylinder head was improved. This fact will later be discussed in more detail.

In figure 2 is plotted the maximum permissible density factor as a function of the estimated end-gas temperature obtained by substituting in equations (1a) and (1b) data from table II for the iso-octane and the iso-octane plus 1.0 ml of tetraethyl lead with the improved cooling. The important fact to be noted from the curves is that, although the data for each fuel were obtained for a variety of compression ratios, inlet-air pressures, and inlet-air temperatures, the data for each fuel can be expressed as a single curve and from this curve various combinations of the three aforementioned variables can be chosen which will represent the maximum conditions at which the engine can be operated without knock.

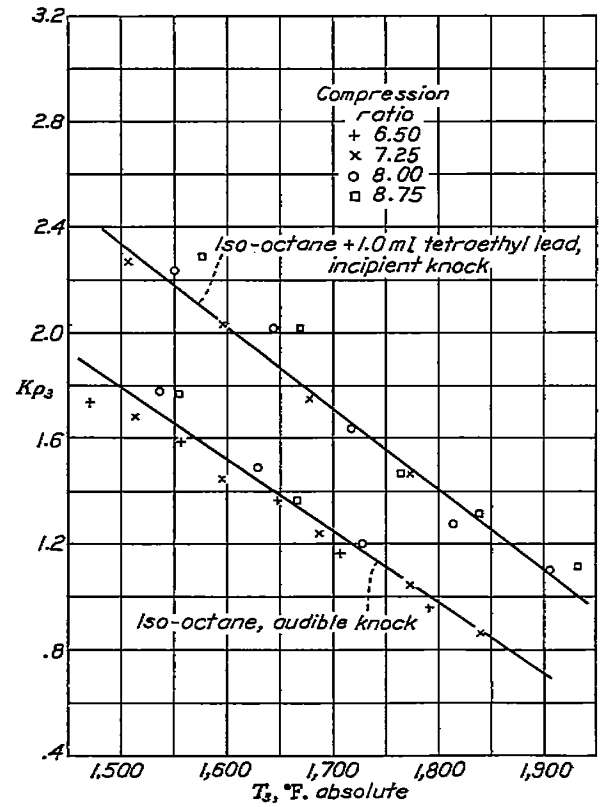

FIGURE 2.—Effect of estimated temperature T_3 of end gas on maximum permissible density factor. Flat-disk combustion chamber; engine speed, 2,500 r. p. m.; improved cooling in cylinder head; fuel-air ratio, 0.081.

The problem of determining the knocking characteristics of the fuel within the engine is simplified if recorded test temperatures and pressures can be used in place of the estimated values shown in figure 2. For the range of values shown in table II, the value of $(1+H/c_vT_1R^{\gamma-1})^{\frac{1}{\gamma}}$ at an inlet-air temperature of 120° F. varied from a value of 3.82 at a compression ratio of 6.5 to a value of 3.62 at a compression ratio of 8.75. Consequently, it is reasonable to assume that, for any given inlet-air temperature, the density factor can be expressed by RP_1/T_1. The value of the expression in the parentheses raised to $(\gamma-1)/\gamma$ shows even less variation, the range being from 1.48 to 1.39 for all the values listed in table II. For practical purposes, the expression in the parentheses can be eliminated from equations (1a) and (2a). The density factor is then expressed by RP_1/T_1

and the temperature factor by $T_1R^{\gamma-1}$. As a further simplification, $R^{\gamma-1}$ will also be eliminated. The deletion of this factor from the temperature expression is justified, not from an analysis of the equation, but from the experimental results as shown in figure 3. In this figure the inlet-air temperature is plotted against the maximum permissible density factor, RP_1/T_1, for the conditions shown in figure 2 together with some check runs. The results show that the data can be expressed in this manner by a straight line for each fuel. Similar curves for all the fuels listed in table II are shown in figure 4.

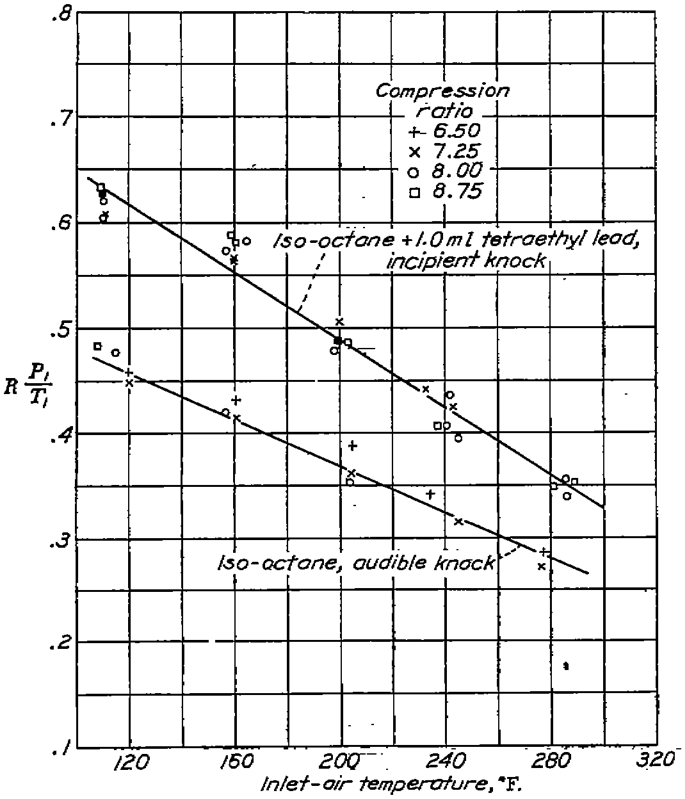

FIGURE 3.—Effect of inlet-air temperature on maximum permissible density factor. Flat-disk combustion chamber; engine speed, 2,500 r. p. m.; improved cooling in center of cylinder head; fuel-air ratio, 0.081.

The improved cooling of the flat-disk cylinder head increased the maximum permissible density factor for the fuel that showed preignition or afterignition but not for the other fuels. This fact indicates that fuels subject to this secondary ignition because of a hot spot in the combustion chamber can be used at more severe engine conditions if this hot spot is removed, whereas fuels that knock without first preigniting or afterigniting are not necessarily improved. A still more important conclusion is that preignition and afterignition are separate phenomena from knock and must be treated as such. It is quite probable that the hot spot in this case appeared only after the heat flow through the cylinder wall had exceeded a certain value and consequently was not present with the fuels of lower knock rating.

The data from table IV for the pent-roof combustion chamber are plotted in figure 5. The deviation of the experimental data from the curves in figure 5 is much less than that in figure 3. Extreme care was taken to decrease the cyclic variation of the spark timing in obtaining the data presented in figure 5. This variation was decreased to $\pm 3/4$ crankshaft degree by mounting the breaker on an extension to the crankshaft.

Plotting the values of RP_1/T_1 against inlet-air temperature instead of compression temperature and using a single curve to represent all compression ratios assumes that, for a given inlet-air temperature, the value of the factor RP_1/T_1 is a constant regardless of compression ratio. The data in figures 3 and 5 indicate that this factor is approximately constant for the engine tested over a range of compression ratios from 6.50 to 8.75. Data obtained by Mucklow (reference 4) on two engines and by Taylor (reference 5) on one engine (table V) over a similar range of compression ratios and for engines of a similar size also show this factor to be approximately constant for a constant inlet-air temperature. These data also indicate that the approximation is justified.

TABLE V

EFFECT OF COMPRESSION RATIO ON ALLOWABLE BOOST PRESSURE. INLET-AIR TEMPERATURE CONSTANT FOR EACH SERIES OF TESTS

Engine	Fuel	Compression ratio	Maximum induction pressure (in. Hg abs.)	$\frac{RP_1}{10}$
Single-cylinder Napier (reference 4).	Petrol	4.5	42.3	19.0
		4.0	54.3	21.7
		3.5	60.8	21.8
Single-cylinder Rolls-Royce (reference 4).	Benzole	4.0	65.4	26.1
		5.0	56.8	28.4
		5.5	51.4	28.3
		6.0	50.9	30.6
		6.5	45.3	29.4
		7.0	41.1	28.8
N. A. C. A. universal test engine (reference 5, fig. 11).	Domestic aviation gasoline.	3.5	44.0	15.4
		4.0	37.5	15.5
		4.5	32.5	15.3
		5.0	30.0	15.5

Boerlage (reference 6) has reported a series of tests on a C. F. R. engine in which the compression ratio and boost pressure were varied to determine the maximum permissible values for a series of fuels from 50 to 100 octane number. The inlet-air temperature was maintained constant at 68° F. Table VI lists the products of the compression ratio by the maximum permissible inlet-air pressure for two of the fuels reported.

For the C. F. R. engine, there is a definite decrease in the maximum permissible density factor for an increasing compression ratio. It seems that, with the

TABLE VI

EFFECT OF COMPRESSION RATIO ON ALLOWABLE BOOST PRESSURE ON C. F. R. ENGINE (REFERENCE 6)

Fuel	Compression ratio	Pressure P_1 (in. Hg abs.)	$\frac{RP_1}{10}$
100 octane number fuel	6.5	45.7	29.7
	7.0	41.0	28.7
	7.5	37.7	28.4
	8.0	34.6	27.7
90 octane number fuel	6.0	41.8	27.1
	6.5	37.0	24.1
	7.0	32.3	22.9
	7.5	29.9	22.5

engines of larger bore, the data for which are given in tables II to V, the effect of the increased temperature caused by increasing the compression ratio is small or is offset by some other factor; whereas, in the smaller engine, the effect of the increased temperature caused by increasing the compression ratio is appreciable. Since the present report is limited to cylinder sizes

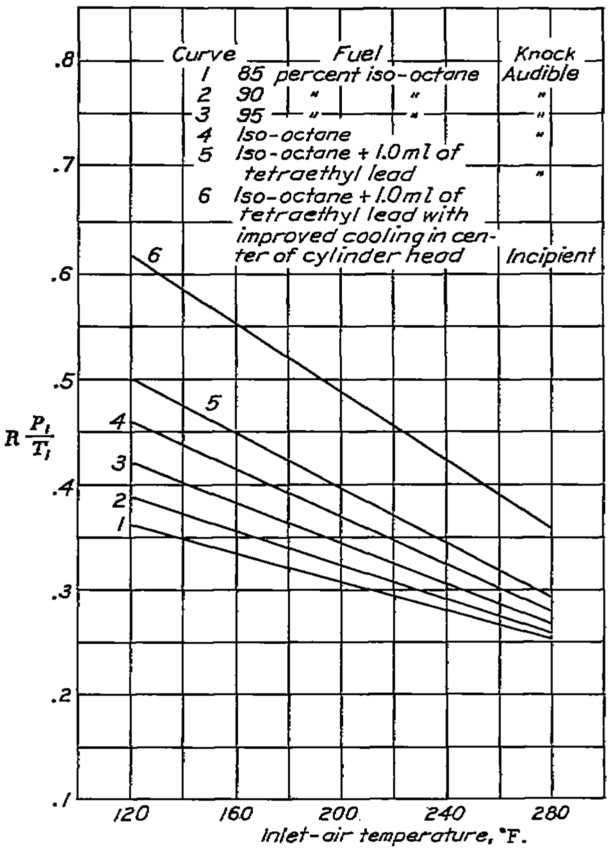

FIGURE 4.—Effect of inlet-air temperature on maximum permissible density factor for a series of fuel blends. Flat-disk combustion chamber; engine-speed, 2,500 r. p. m.; fuel-air ratio, 0.081.

suitable for aircraft engines of high power output, the assumption will be made that the maximum permissible value of RP_1/T_1 is a constant regardless of compression ratio. It is emphasized, however, that more experimental data are necessary fully to justify this assumption. In either case, the principles upon which the analysis is based are equally applicable, the point at issue being whether the inlet-air temperature can be taken as the abscissa of the rating curve or whether some other temperature in the cycle, such as the estimated end-gas temperature, must be used.

As is to be expected, the curves in figures 3 and 5 are similar on account of the similarity of the fuels. The curves bring out clearly the limits at which each fuel can be operated and the temperature susceptibility of the fuels. The curves present the knocking characteristics of the fuels in a more satisfactory manner than could be done by any single value. For instance, the data indicate that the leaded fuel should be capable of operation at a compression ratio of about 12, provided that the inlet-air temperature does not exceed 120° F. and the inlet-air pressure does not exceed 30 inches of mercury absolute.

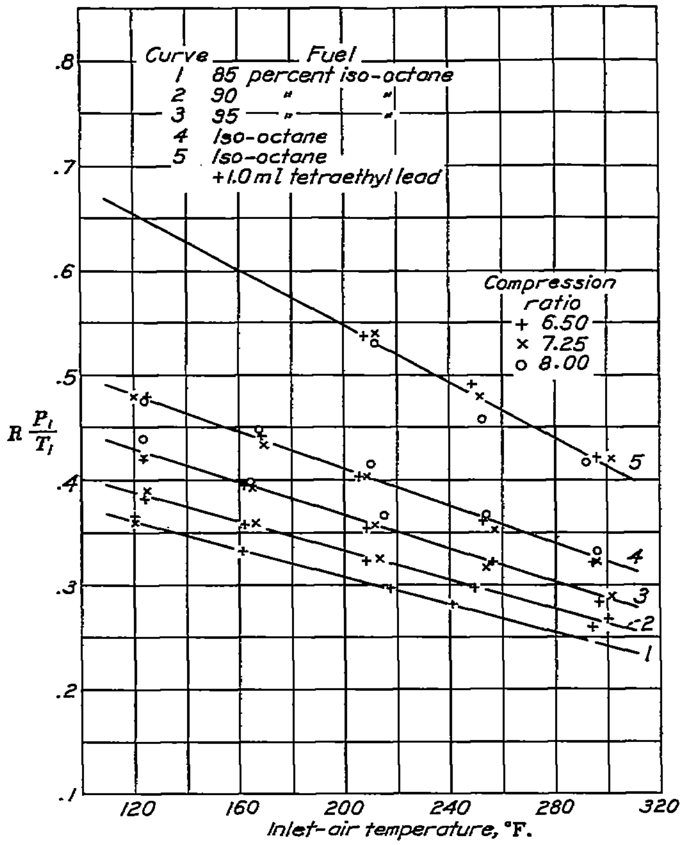

FIGURE 5.—Effect of inlet-air temperature on maximum permissible density factor for a series of fuel blends. Pent-roof combustion chamber; engine speed, 2,500 r. p. m.; fuel-air ratio, 0.078; incipient knock.

As has been previously stated, the rating curve could have been obtained from the peak combustion pressures rather than the compression ratio. In table VII the values for the 95 percent iso-octane used under the conditions listed in table IV are given. From these data, the values of $K\rho_3$ and T_3 are computed from equations (1) and (2). The value of γ is estimated to be 1.29 for the compression of the unburned mixture. This value is based on experimental investigations of cycle efficiencies. The results are shown in figure 6. Because of the difficulty of accurately measuring the peak pressures, it is not to be expected that the results will show the same uniformity as is the case with the data in figure 5. The data, nevertheless, show a definite relation between the estimated peak temperature and the estimated peak density for the condition of incipient knock regardless of the engine conditions used to obtain the knock.

The values in the last column of table VII are the values of peak pressures estimated from the curve in figure 6; that is, they are the peak pressures that give values of ρ_3 and T_3 which will lie on the curve of figure 6.

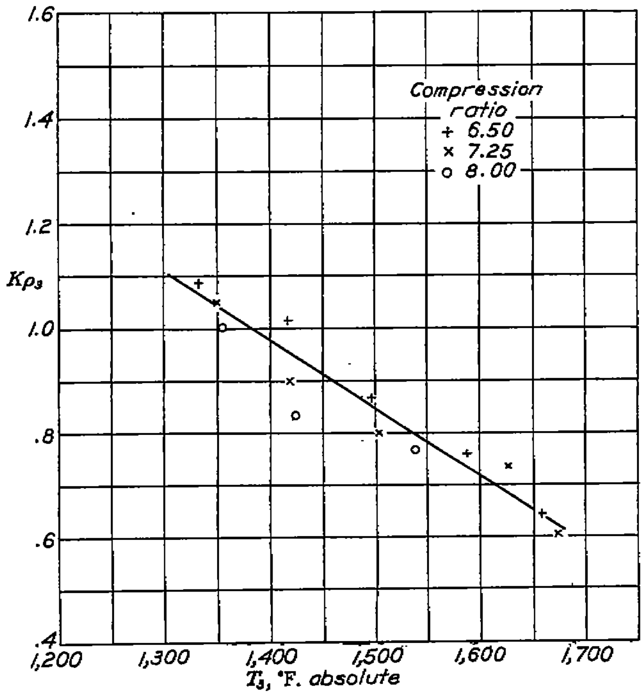

FIGURE 6.—Rating curve determined from peak pressure, inlet-air pressure, and inlet-air temperature. Fuel, 95 percent iso-octane; γ, 1.29. (See table VII.)

TABLE VII

EFFECT OF INLET-AIR TEMPERATURE AND INLET-AIR PRESSURE ON MAXIMUM PERMISSIBLE PEAK PRESSURE

[Engine speed, 2,500 r. p. m.; fuel, 95 percent iso-octane; knock, incipient; pent-roof combustion chamber]

Compression ratio	T_1 (°F. abs.)	P_1 (in Hg abs.)	P_3 (lb. per sq. in.)	
			Recorded	Estimated from fig. 6
6.50	584	37.9	720	710
	622	37.8	720	680
	669	36.4	650	640
	717	35.6	600	590
	757	33.2	530	530
7.25	584	34.2	700	700
	625	33.8	630	670
	671	33.1	600	620
	714	31.2	590	570
	761	30.8	500	510
8.00	583	32.2	675	700
	624	31.0	590	660
	675	31.1	590	610

EFFECT OF JACKET OR COOLANT TEMPERATURE

Tests of fuels in which the coolant temperature (T_c) is varied should be capable of similar analysis provided that the coolant temperature is used in place of the inlet-air temperature. It is probable that cylinder-wall temperature is of more significance than coolant temperature. Figure 7 shows results computed from data obtained by Edgar with different benzene blends (reference 7), using the coolant temperature. In these tests, the inlet-air temperature and pressure were maintained constant, and the coolant temperature and the compression ratio were varied. The data indicate that the effect on the maximum permissible density factor of the coolant temperature is of the same order of magnitude as the effect of inlet-air temperature.

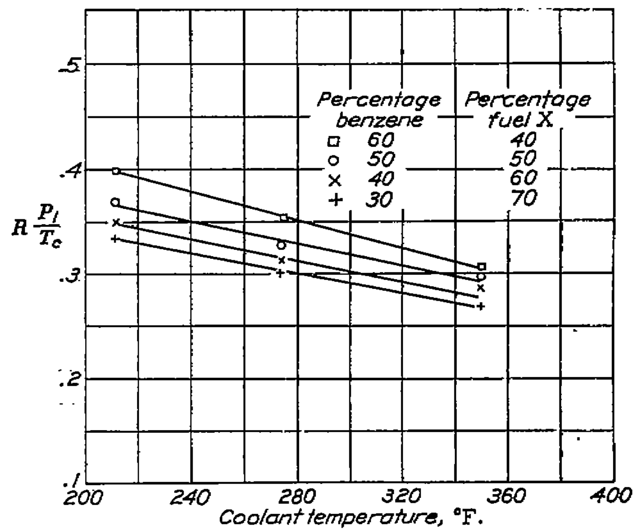

FIGURE 7.—Effect of coolant temperature on maximum permissible density factor (data from reference 7). C. F. R. engine at 600 r. p. m.; inlet-air pressure, atmospheric; 30 inches Hg assumed. Inlet-air temperature varied from 68° to 78° F.

VARIATION OF KNOCKING CHARACTERISTICS OF DIFFERENT FUELS

Kurtz (reference 8) has presented data on the maximum permissible inlet pressure as a function of charge temperature on a single-cylinder test engine at a compression ratio of 6. His results for three fuels have been replotted in figure 8. The data can be satisfactorily represented by straight lines. The curves show that, at a temperature of 100° F., xylol and the blended fuel have the same rating; whereas, at 300° F., the blended fuel and "iso-octane 95" have the same rating. The curves illustrate the different slopes that may occur with different fuels, as suggested in figure 1.

A rather extensive series of tests has recently been completed by Heron and Gillig (reference 9) in which the maximum permissible inlet-air pressure was determined for different fuel blends and chemical compounds at two engine coolant temperatures and two engine speeds. These data are made particularly significant by the fact that Heron and Gillig carefully distinguish between knock and preignition or afterignition. Figure 9 shows their results for mixtures of C. F. R. S-1 reference fuel and C. F. R. M-1 reference fuel. The octane numbers of these blends (C. F. R. method) are within one octane number of the corresponding blends presented in tables II to IV. Because only two points are given, the curves are drawn as straight lines. In each case the maximum permissible inlet-air pressure was limited by knock.

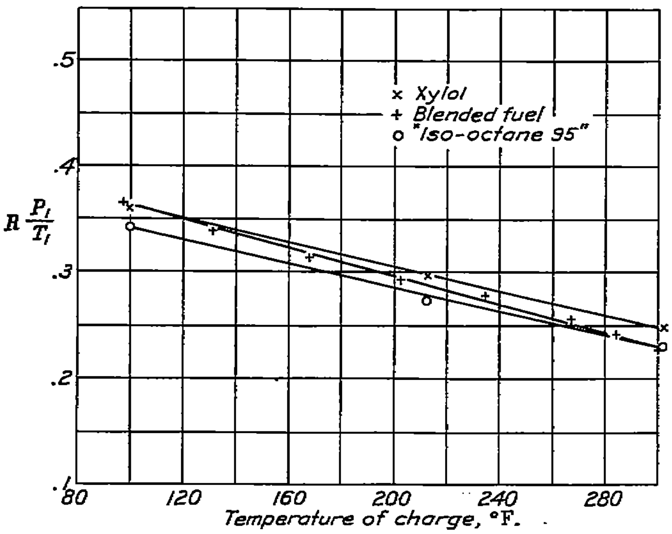

FIGURE 8.—Effect of temperature of charge on maximum permissible density factor for three different fuels (data from reference 8).

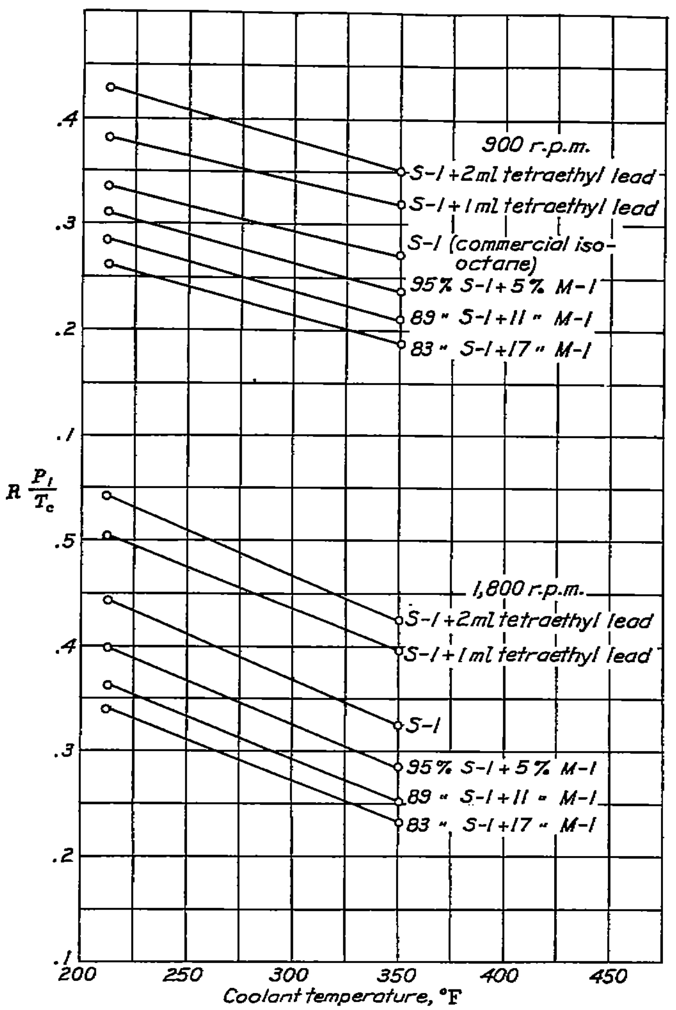

FIGURE 9.—Effect of coolant temperature on maximum permissible density factor (data from reference 9). C. F. R. engine; compression ratio, 5.5; inlet-air temperature, 80°–95° F.

Figure 10 shows the wide divergence that may be expected for performance of different fuels under a variety of engine conditions. The factor that was the cause of limiting the maximum permissible inlet-air pressure is indicated for each fuel. Toluene and benzene have curves that are somewhat similar, as might be expected. Iso-octane and di-isopropyl ether have curves which are even more similar but which bear no

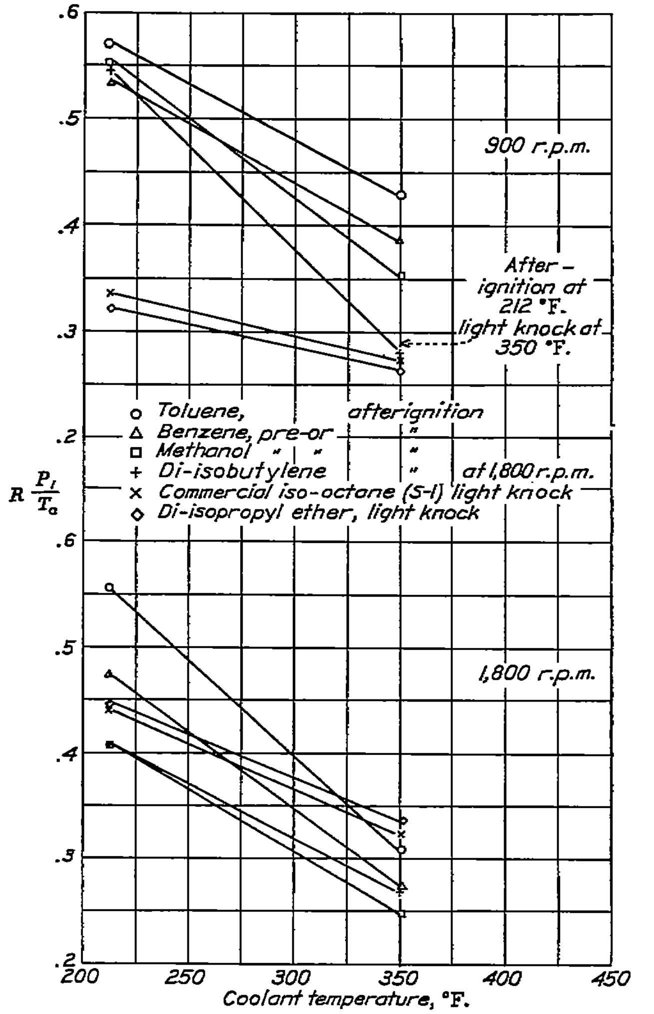

FIGURE 10.—Effect of coolant temperature on maximum permissible density factor for various chemical compounds (data from reference 9). C. F. R. engine; compression ratio, 5.5; inlet-air temperature, 80°–95° F.

relation to those for benzene and toluene, benzene and toluene showing a much greater degree of temperature variation. At 1,800 r. p. m. and at the lower coolant temperature, benzene and toluene are superior to any of the others listed, but they are inferior to either iso-octane or di-isopropyl ether at the higher temperature. The fuels that were subject to preignition or afterignition showed much more dependency on the coolant temperature than did those that knocked. This fact is in agreement with the analysis presented in the first part of this discussion. The differences between the curves for the two speeds will be discussed later.

EFFECT OF FUEL-AIR RATIO

The effect of fuel-air ratio on the knocking characteristics of a fuel depends both on the changes in the chemical mixture and the changes in the temperature of the charge just before knock or secondary ignition. Boerlage (reference 6) has shown the maximum permissible inlet-air pressure as a function of fuel-air ratio (fig. 11). In these tests, the maximum permissible inlet-air pressure was a minimum at the mixture ratio corresponding to the maximum cylinder temperature and exhaust-gas temperature. These maximum temperatures occurred at a mixture ratio near the chemically correct value.

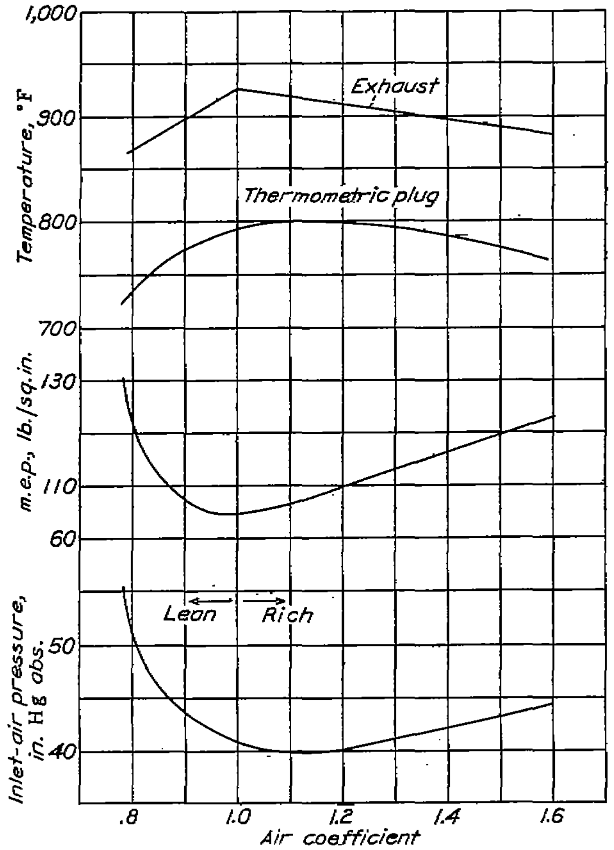

FIGURE 11.—Relation between mixture ratio and maximum permissible inlet-air pressure and m. e. p. and between mixture ratio and cylinder- and exhaust-gas temperature (curves from reference 6).

MacClain and Buck (reference 10) have shown that, for constant power, the cylinder temperatures reach a maximum and then decrease as the mixture is leaned and the manifold pressure is increased to maintain the specified power. This fact, in conjunction with Boerlage's data (fig. 11), which show that for a constant degree of knock the increase in maximum permissible inlet-air pressure permits an appreciable increase in power with the lean mixtures, indicates that an increasing amount of interest should be shown in the operation of aircraft engines at mixtures leaner than the chemically correct mixture.

Figure 12 shows the effect of fuel-air ratio on the maximum permissible density factor and on the specific fuel consumption for the pent-roof combustion chamber, for which other data have already been given in table IV. The fuel-air ratio for the data in table IV (0.078) was the ratio giving maximum knock. The curves in figure 12 show that this ratio has the lowest permissible maximum density factor. When the curves are cross-plotted, as in figure 13, it is seen that, from a fuel-air ratio of 0.080 to one of 0.140, each increase of 0.02 in the ratio permits the same increase in the density factor as a decrease of 40° F. in the inlet-air

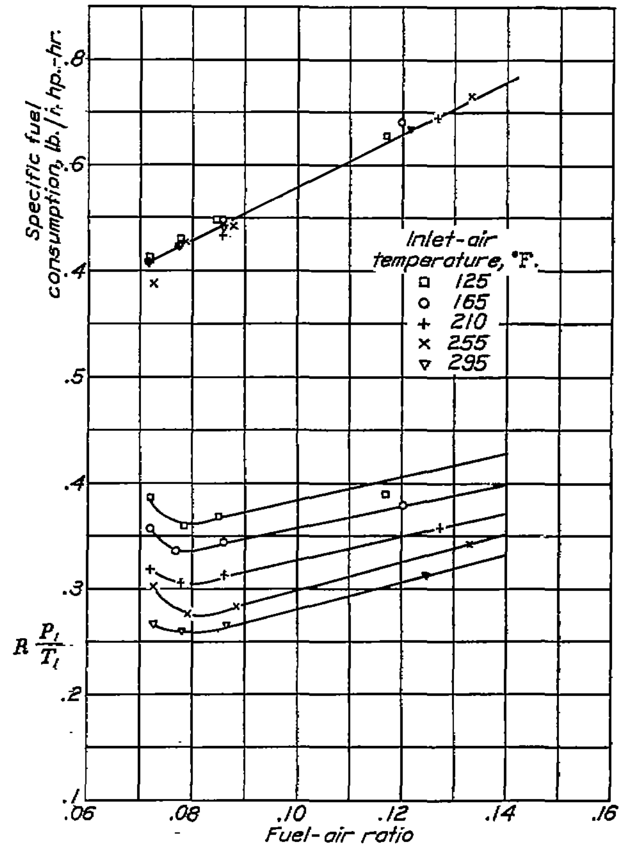

FIGURE 12.—Effect of fuel-air ratio on maximum permissible density factor and specific fuel consumption. Pent-roof combustion chamber; engine speed, 2,500 r. p. m.; 85 percent iso-octane; compression ratio, 6.5; incipient knock.

temperature. Tests of additional fuels are necessary to obtain a general conclusion relative to the numerical effects of fuel-air ratio. Within the range of fuels used in aircraft, this effect may be independent of the fuel.

In figure 11 it is shown that, even though the maximum permissible power increases at fuel-air ratios richer or leaner than the correct, the measured engine temperatures decreased. This fact indicates that the cooling effects of the excess fuel or the excess air more than compensated for the increased rate of heat transfer resulting from the increased density of charge accompanying the higher inlet-air pressures. Further information on the actual end-gas temperatures and densities for the condition of incipient knock is given in figure 14, in which values of $K\rho_3$ and of T_3 obtained from figure 12 and equations (1a) and (2a) are given. Figure 14 shows that the maximum permissible end-gas density at any given end-gas temperature decreases as the fuel-air ratio is increased. This effect is to be expected from researches on combustion. Peletier, for example, has shown in reference 11 that the highest permissible compression ratio without auto-ignition decreased from 9 at a fuel-air ratio of about 0.020 to a

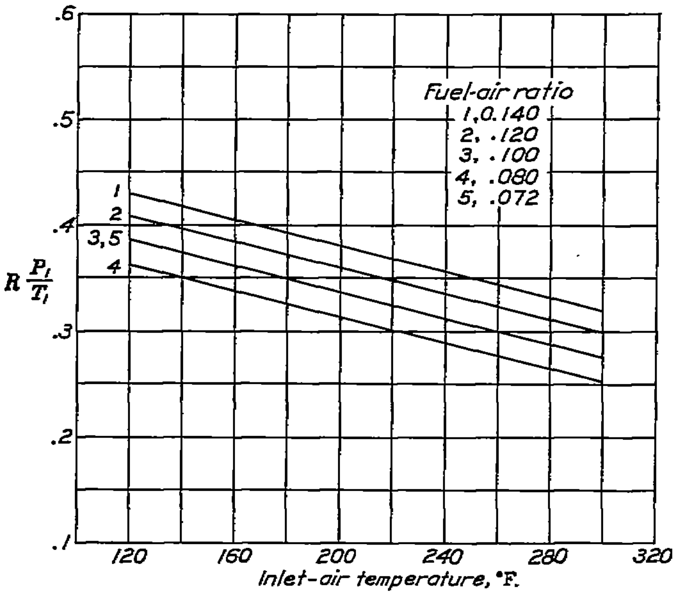

FIGURE 13.—Effect of inlet-air temperature on maximum permissible inlet density factor at a series of fuel-air ratios. Pent-roof combustion chamber; engine speed, 2,500 r. p. m.; 85 percent iso-octane; compression ratio, 6.5; incipient knock.

minimum of 6 at a fuel-air ratio of about 0.11. The data in figures 13 and 14 show that, for equal end-gas temperatures and densities, knock increases as the mixture becomes richer but that, in the engine, the cooling effects of excess air or of excess fuel are sufficiently great so that higher inlet-air densities can be used as the mixture ratio is either increased or decreased from the approximately chemically correct mixture.

In the determination of the curves in figure 14, it was necessary to express the variation of H as a function of fuel-air ratio since H appears both in equation (1a) and in equation (2a). It was assumed that the value of H was expressed by

$$H=\frac{E_{com}\times 18000\times \text{mass of fuel}}{\text{mass of fuel}+\text{mass of air}}$$

$$=\frac{E_{com}\times 18000\times F}{1+F} \tag{3}$$

in which F is the fuel-air ratio. Values of E_{com}, the combustion efficiency, were obtained from the test data given by Gerrish and Voss in reference 12.

EFFECT OF HUMIDITY

Humidity of the inlet air has two effects on the combustion: It changes the chemical constituents of the mixture, and it introduces a heat absorbent in the form of water vapor. In the N. A. C. A. tests already presented, although no attempt was made to keep the humidity constant, the indications are that the effect of humidity is small. There is a great deal of data available on the effect of humidity on knock rating of fuels by octane number, but most of these data are difficult to place on an absolute basis such as described in this report.

Stansfield and Thole (reference 13) have presented the results of tests in which they determined the effect of humidity on the highest useful compression ratio for a series of fuels. They state that the effect of humidity up to saturation at 65° F. is unimportant and that, if the proportion of water vapor is greater, a correction is

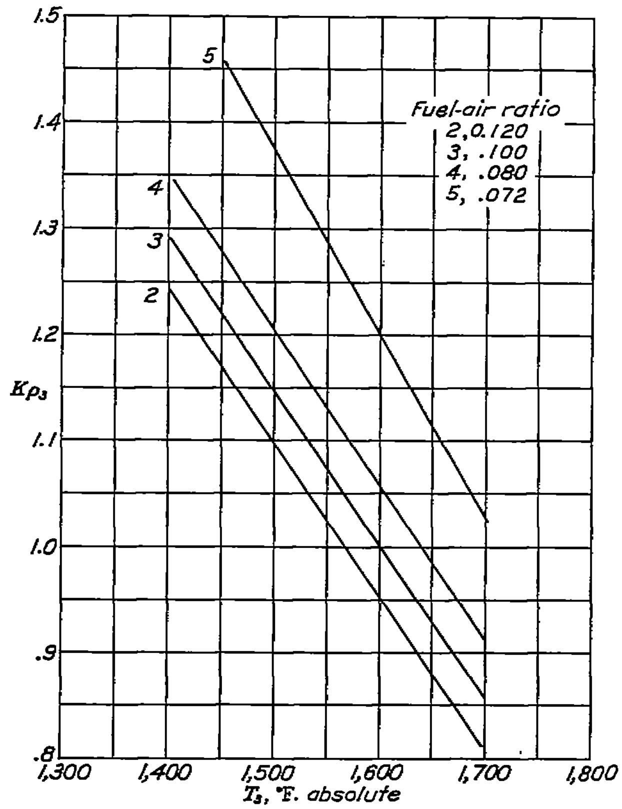

FIGURE 14.—Effect of end-gas temperature on maximum permissible end-gas density for incipient knock for a series of fuel-air ratios. Pent-roof combustion chamber; engine speed, 2,500 r. p. m.; 85 percent iso-octane; compression ratio, 6.5.

necessary for certain fuels when results of a high order of accuracy are required. They also found that water vapor up to 50 percent of the fuel weight raised the highest useful compression ratio by 0.55. Computations indicate that this quantity of water vapor decreases the compression temperature 40° F. This decrease in compression temperature corresponds to a decrease of about 15° F. in the temperature at the start of compression. At 100° F. and 29.92 inches of mercury absolute pressure, the water-air ratio for saturation is 0.048. Since water vapor absorbs heat, it is to be expected that the knocking fuels which show the greatest temperature variation will show the greatest increase in maximum permissible density factor for a given amount of water vapor or for a given amount of water introduced into the fuel-air mixture. If the presence of the water vapor has any chemical effect on the combustion, it must be determined by test. There are at present, however, no indications that such chemical effects exist within the range of fuels or engine conditions used in operation.

EFFECT OF EXHAUST-GAS DILUTION

Exhaust-gas dilution generally increases the temperature of the mixture to a degree depending on the percentage of exhaust gases remaining in the cylinder following the scavenging stroke. Computations indicate that doubling the percentage of exhaust gas remaining in the cylinder over that normally experienced at full throttle increases the temperature at the beginning of compression 60° F. and at the end of compression 100° F. In a throttled engine, the exhaust-gas dilution may be increased to a sufficient amount to affect also the maximum permissible density factor on the basis of decreasing the fuel-gas ratio.

Some interesting data on the effect of exhaust-gas dilution are presented by Tizard in reference 14. These data show that, when a test engine was throttled, the maximum permissible density factor based on the fresh charge inducted was decreased from 0.49 to 0.26 for a decrease in initial charge from 1.00 to 0.54. Introducing the exhaust gas with the incoming air and at the same temperature as the air permitted the maximum permissible density factor, based on the fuel-air mixture inducted, to be increased from 0.49 to 0.62 for an addition of from 0 to 15 percent exhaust gas in the mixture. The data show that the effect of the exhaust gas itself is to increase the maximum permissible density factor probably in the same manner that the water vapor increases this factor by acting as a heat absorbent. In throttling, however, this density effect is more than offset by the increased resultant temperature of the gases. In actual service engines, it is doubtful if the effect of exhaust gas need be considered unless comparison is being made with an engine that is completely scavenged or one using a turbosupercharger for boosting at sea level. The results of the N. A. C. A. tests presented in this report gave satisfactory knock-rating curves even though the percentage of exhaust-gas content varied by about 2:1.

EFFECT OF ENGINE SPEED

The effect of engine speed is twofold. Increasing the speed decreases the time interval for heat exchange between the inducted charge and the walls of the cylinder and the combustion chamber and decreases the induction time preceding ignition by the electric spark during which precombustion reactions may take place within the fuel-air charge. The difference in time interval for heat transfer to the charge changes not only the temperature of the charge but also the density at any given inlet-air temperature and density.

Data obtained by Heron and Gillig (reference 9) show that, with the C. F. R. engine used by them at any given inlet-air pressure, the indicated mean effective pressure at a coolant temperature of 212° F. did not change for an increase of speed from 900 to 1,800 r. p. m. When the coolant temperature was increased to 350° F., the indicated mean effective pressure at 900 r. p. m. decreased 15 percent and, at 1,800 r. p. m., decreased only 6 percent. In these tests the spark advance was 30° B. T. C.

Figure 15 shows the data from reference 9 for the two engine speeds; again straight lines have been drawn connecting the two points for each fuel. The most interesting fact obtained from figure 15 is that, with the exception of S–1 plus tetraethyl lead (which afterignited), the fuels which knocked appreciated with engine speed and the fuels which preignited or afterignited depreciated with engine speed. This fact again indicates that secondary ignition is a different phenomenon from knock and must be so recognized.

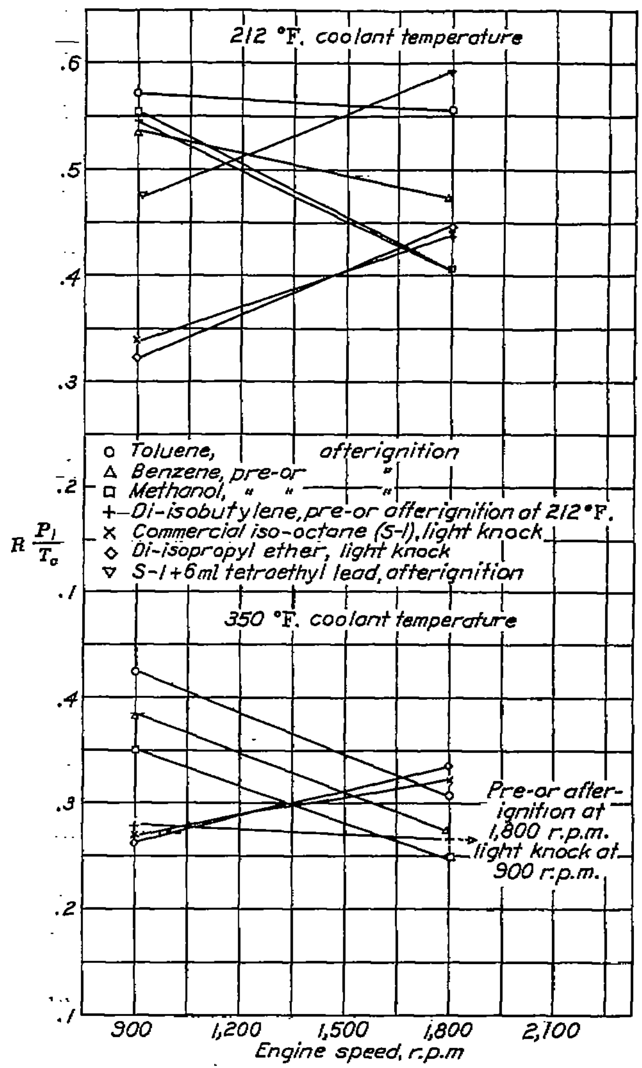

FIGURE 15.—Effect of engine speed on maximum permissible density factor for various chemical compounds (data from reference 9). C. F. R. engine; compression ratio, 5.5; inlet-air temperature, 80°–95° F.

The cause of the depreciation with speed of the secondary igniting fuels may be chemical, and the explanation may be that decreasing the induction period for precombustion reactions favors the formation of certain compounds which lead to secondary ignition. A more likely explanation is that, since increasing the speed increases the total heat flow through the cylinder walls, it increases the temperature of any hot spot to a greater extent than it increases the temperature of the rest of the walls.

The fact that the knocking fuels appreciated with engine speed may be the result of the increased rate of burning at the higher speed or it may be a temperature spark effect. The true effect of speed on knock should be determined by the use of the optimum spark advance at each speed tested. In this manner, the effect of engine speed together with the effect of heat transfer during the induction and the compression strokes will be determined. The speed and the heat-transfer effects should be partly separated by maintaining the cylinder-wall temperature constant and by measuring the mass of air inducted at each inlet-air temperature rather than the inlet-air pressure.

Heron and Gillig in subsequent tests (unpublished) found that using a sodium-cooled piston permitted the boost pressure to be increased 32 percent with benzene but only 3 percent with S–1 fuel. They also found that, with this piston and a coolant temperature of 350° F. at an engine speed of 1,800 r. p. m. and inlet-air temperatures of 100° and 212° F., benzene permitted a boost 6 percent higher than that permitted by S–1, and that benzene (which was limited by preignition or after-ignition) was very sensitive to spark-plug condition whereas S–1 was not. These data indicate that knocking fuels are inherently less sensitive than preigniting fuels to the uniformity of engine temperature.

EFFECT OF SPARK ADVANCE

Varying the spark advance has the effect of varying the temperature and the density at the time of knock. Therefore varying the spark advance has much the same effect as varying the compression ratio. It is to be expected that all fuels will not react the same to changes in spark advance because of the variation in the temperature-density relationship of the different fuels.

The effect of varying the compression ratio on the knock rating of the fuel in an engine has been shown to be an effect chiefly of changing the gas density. As the compression ratio is increased above the maximum permissible value for any inlet-air condition, retarding the spark to prevent knock should decrease the effective compression ratio to the value that was found to be permissible. The same idea can be expressed in a different manner by saying that, for any given condition of inlet-air temperature and pressure, the maximum permissible power output should be independent of compression ratio provided that the ignition spark is sufficiently retarded to prevent knock and the spark advance is equal to or less than the value required for optimum advance. That this fact is approximately true is shown in figure 16 from tests reported by Gardiner and Whedon (reference 15). In this figure the broken curve shows the effect of compression ratio on the indicated mean effective pressure of the engine tested for a nonknocking fuel and a constant spark advance. The solid curves are for the same engine operating on a gasoline that knocked at a compression ratio of 4.7. As the compression ratio was increased above this value and the spark retarded so that the knock was maintained at a constant level, the indicated mean effective pressure remained practically constant.

Data showing the permissible increase in inlet-air pressure with a retarded spark (reference 16) are shown in figure 17. The optimum spark advance in this case was 29°. The data represent an effective decrease in the compression ratio caused by the retarded spark

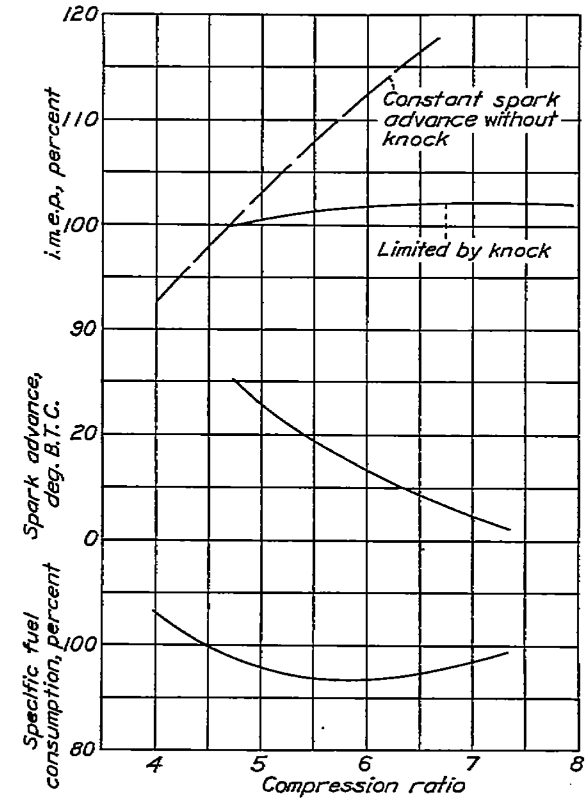

FIGURE 16.—Relationship between compression ratio and engine performance with spark advance adjusted for a constant degree of knock (curves from reference 15).

with the accompanying increase in the permissible boost pressure.

EFFECT OF ENGINE DESIGN

The effect of engine design (such as combustion-chamber shape, turbulence, spark-plug position, bore-stroke ratio, cooling medium, effectiveness of the cooling, and size) has many ramifications. Probably the more important effects to be considered are the time required for completion of combustion, the surface-volume ratio of the combustion chamber, and the uniformity of the cooling of the walls of the cylinder and the combustion chamber.

The surface-volume ratio is important from considerations of the cooling of the gases during the induction and combustion periods. This ratio will probably not in itself affect fuels that preignite, uniform cooling of the combustion chamber being assumed, and will probably affect knocking fuels. As the ratio is increased, the heat flow between the gases and the metal walls is increased, which, in turn, affects the end-gas temperatures and consequently the maximum permissible density factor.

Decreasing the engine size will tend to increase the charge temperature if the wall is at a higher temperature than the incoming charge and to decrease the charge temperature if the wall is at a lower temperature

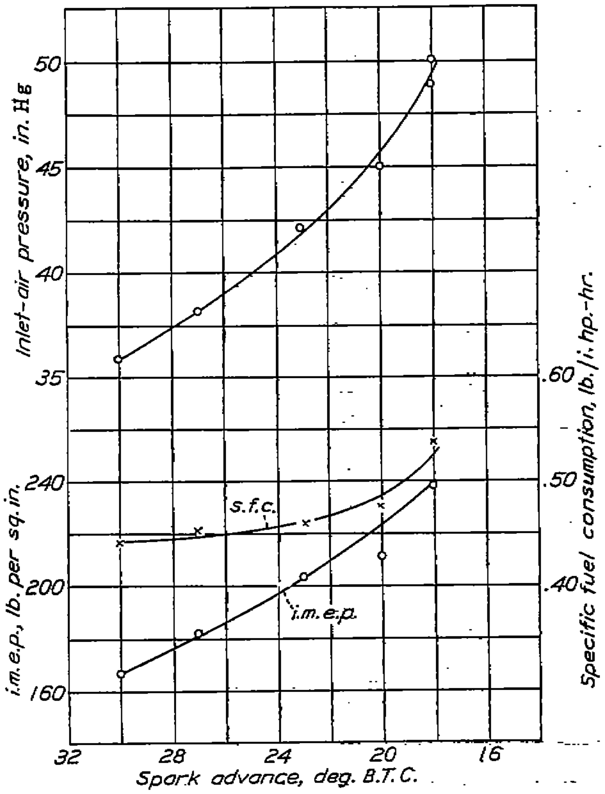

FIGURE 17.—Effect of spark advance on maximum permissible inlet-air pressure and on maximum permissible i. m. e. p. (data from reference 16). Engine speed 2,500 r. p. m; iso-octane+ml tetraethyl lead; compression ratio, 8.0; inlet-air temperature, 200° F.

than that of the incoming charge. With preigniting or afterigniting fuels, it is probable that changing the engine dimensions will not have much effect other than that produced by the temperature change. Additional experimental evidence is necessary on this point.

Hawley and Bartholomew have presented data on the effect of bore and stroke on highest useful compression ratio (reference 17). Their data show this ratio to decrease as either the bore or the stroke is increased but the rate of decrease to become less at the larger bores.

The uniformity of the cooling of the combustion-chamber walls and the occurrence of hot spots within the combustion chamber are particularly important in that hot spots may cause a fuel to preignite at a lower value of the charge density factor than would have been the case had the fuel been limited by knock. This action occurred in the N. A. C. A. tests, the results of which have already been presented in table II. Aircraft engines probably show considerable variation from any single standard because of variations in method and uniformity of cooling. Hot spots produced by exhaust valves and by spark plugs vary considerably between engines. The uniformity of the cooling of the cylinder head depends on both the cooling medium and the efficiency with which the medium is brought into contact with the metal of the cylinder and the cylinder head. A comparison of the rating curves in figures 4 and 5 gives additional information on the effects of engine design. The relationship of these two sets of data will be discussed in more detail in the section on correlation of data.

Turbulence or air flow in the combustion chamber is known to affect knock, but the manner in which its effect is produced is not known and must be the subject of further investigation.

From the foregoing analyses, it is evident that a single curve expresses the knocking characteristics of a fuel in any one engine for a large range of engine operating conditions. For a given engine, this curve can be obtained from a series of runs at one compression ratio and various inlet-air pressures and temperatures or from a series of runs at one inlet-air pressure and a series of compression ratios and inlet-air temperatures. In either case, the results represent a wide range of the three variables. Once the rating curve of the fuel has been determined, the next problem is to estimate the maximum permissible performance of the engine with this fuel under different operating conditions.

II—DETERMINATION OF MAXIMUM PERMISSIBLE ENGINE PERFORMANCE

The maximum permissible performance obtainable from any engine using a given fuel depends on the service in which the engine is to be used. The requirements for a long-range flying boat are different from those of a transport airplane flying comparatively short distances. The two factors that are probably of most interest in this respect are maximum permissible indicated mean effective pressure and minimum permissible fuel consumption. Peak pressures are of interest from considerations of engine reliability. These three factors are all dependent on the compression ratio of the engine once the maximum permissible density factor is obtained.

In the succeeding analysis, the dependency of the factors will be presented as a function of compression ratio for conditions of intercooling (constant inlet-air temperature) and of no or partial intercooling between the supercharger and the engine cylinders (variable inlet-air temperature).

CONSTANT INLET-AIR TEMPERATURE

The indicated mean effective pressure for a constant fuel-air ratio varies directly as the inlet-air density and the cycle efficiency:

$$\text{i. m. e. p.} \propto \rho_1 \times E_c \tag{4}$$

in which ρ_1 is the inlet-air density and E_c is the cycle efficiency. The inlet-air density is proportional to P_1/T_1. The relationship between RP_1/T_1 at a constant compression ratio and the indicated mean effective pressure is given in figure 18. These data are for the conditions listed in table IV at a compression ratio of 6.50. It is seen that assuming i. m. e. p.$\propto\rho_1\propto P_1/T_1$ introduces a deviation of about ±3 percent. The data presented in the previous section indicate that, for any given fuel and for a constant inlet-air temperature, the product of the inlet-air density times the compression ratio must not exceed a certain constant in order to prevent knock, the value of the constant being dependent on the particular engine. The maximum permissible inlet-air density for any given compression ratio is therefore expressed by:

$$R\rho_1 = K \tag{5}$$

The value of the constant K at any specified inlet-air temperature is determined by the rating curve of the fuel under consideration. Multiplying the right-hand side of proportionality (4) by R/R and eliminating the constant $R\rho_1$, it is seen that

$$\text{i. m. e. p.} \propto \frac{E_c}{R} \tag{6}$$

Therefore, for a given fuel at a given inlet-air temperature, the maximum permissible indicated mean effective pressure varies directly as the cycle efficiency and inversely as the compression ratio. Values of E_c can be determined by computation, taking into account the variation of the specific heats of the gases with temperature and considering the effect of the residual gases. Such computations give the values listed in table VIII for the cycle efficiencies and for the indicated specific fuel consumption in pounds of fuel per indicated horsepower-hour.

TABLE VIII

ESTIMATED CYCLE EFFICIENCIES AND SPECIFIC FUEL CONSUMPTION

Compression ratio	Cycle efficiency	Specific fuel consumption (lb./i. hp.-hr.)
4	0.341	0.408
6	.415	.335
8	.467	.298
10	.500	.278
12	.528	.263

It must be remembered that the values of the cycle efficiencies and the fuel consumptions listed in table VIII do not consider the heat losses during the combustion cycle; consequently, the indicated fuel consumptions obtained on an engine are in excess of the values listed. The values are satisfactory for a comparison. From table VIII and expressions (6) and (5), factors proportional to the maximum permissible indicated mean effective pressure and the maximum permissible boost pressure can be obtained for any inlet-air temperature.

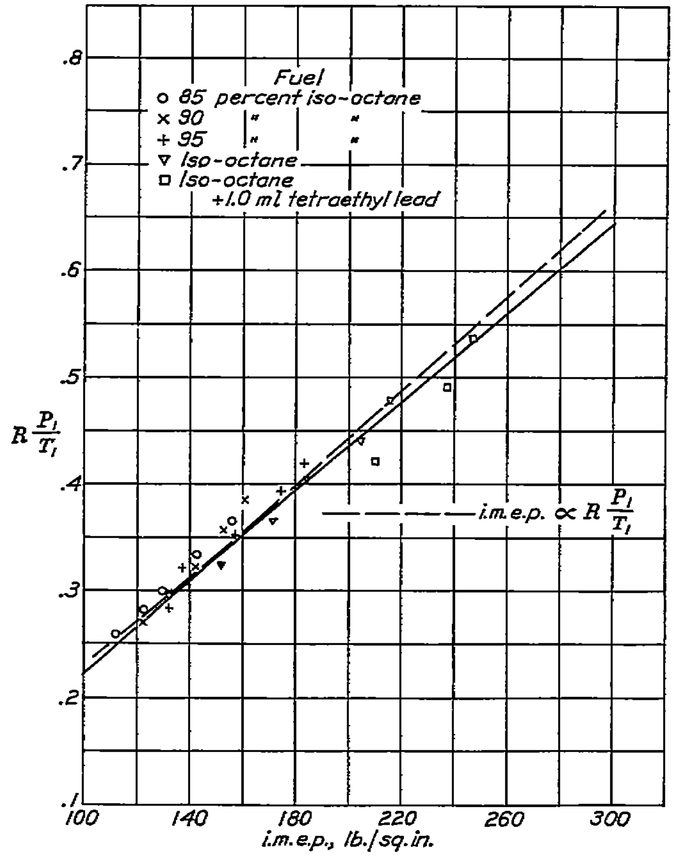

FIGURE 18.—Relationship between indicated mean effective pressure and density factor. Pent-roof combustion chamber; engine speed, 2,500 r. p. m.; fuel-air ratio, 0.078; compression ratio, 6.5; incipient knock; coolant temperature, 250° F.

The maximum permissible peak pressure at any given inlet-air temperature can be estimated from the thermodynamic equation:

$$P_3 = P_1\left(R^\gamma + \frac{R}{T_1} \times \frac{H}{c_v}\right) \tag{7}$$

As has already been shown, for any constant inlet-air temperature, P_1R must be a constant. Equation (7) can then be written as the following proportionality:

$$P_3 \propto \left(R^{\gamma-1} + \frac{H}{T_1 c_v}\right) \tag{8}$$

Assuming a value of 18,000 B. t. u. per pound of fuel, 580° F. absolute for T_1, 0.25 B. t. u. per pound per degree Fahrenheit for c_v, and a fuel-air ratio of 0.069, the proportionality becomes:

$$P_3 \propto R^{\gamma-1} + 8.0 \tag{9}$$

These relationships, assuming a value of 1.29 for γ in expression (9), are shown graphically in figure 19. The values for the indicated mean effective pressure

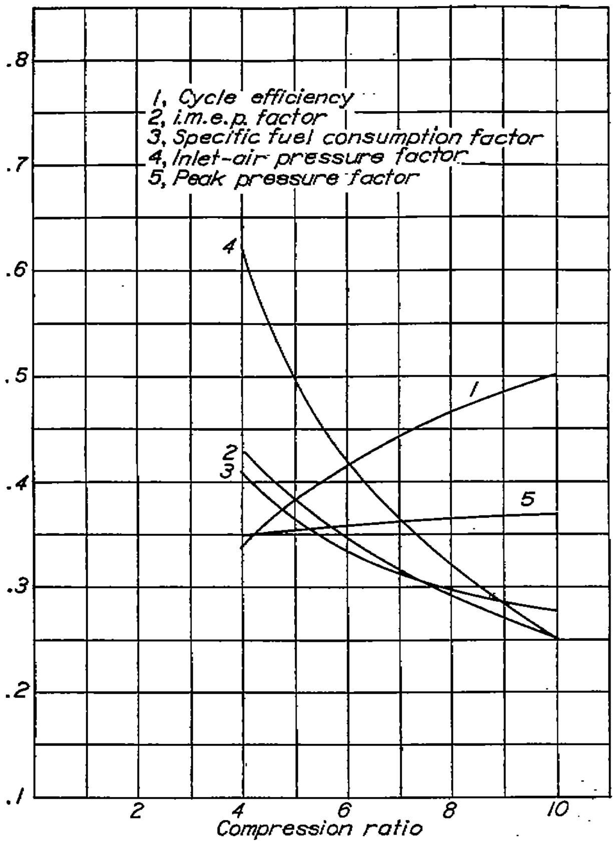

FIGURE 19.—Effect of compression ratio on maximum permissible performance factors.

factor and the peak pressure factor have been multiplied by suitable constants so that the same ordinate scale can be used for all the curves. These curves express the relationship between the maximum permissible indicated mean effective pressure, the lowest permissible indicated specific fuel consumption, and the peak pressure for any one fuel at any one inlet-air temperature for a series of compression ratios. The curve for the necessary inlet-air pressure for the maximum permissible indicated mean effective pressure factor is also given and is proportional to the reciprocal of the compression ratio. It is emphasized again that these curves represent any fuel at any given inlet-air temperature. The results for any two fuels have the same relation as the respective values of RP_1/T_1 for the assumed inlet-air temperature. Curve 5 shows that the estimated maximum permissible peak pressure increases slightly with compression ratio, whereas the data in table VII show that the peak pressures decrease slightly.

VARIABLE INLET-AIR TEMPERATURE

For an engine in which the mixture is not cooled to atmospheric temperature after passing through the supercharger, the effects of the heating of the air during the compression in the supercharger must be taken into account. In the discussion of the previous section in which a constant inlet-air temperature was assumed, it was also assumed that the variation in compression temperature because of the change in compression ratio was negligible. Although this assumption is justified by the data already presented, it is doubtful that it can also be applied to the compression in the supercharger.

An exponent of 1.4 for the compression of the air in the supercharger and an initial air temperature of 120° F. being assumed, the values listed in table IX are obtained for the supercharger compression ratio R_s and for T_1, over a range of P_1 from 30 to 58 inches of mercury absolute. In the fourth column are tabulated the values of RP_1/T_1 for iso-octane, these values having been obtained from column 3 in table IX and figure 4. The fifth column lists the maximum permissible compression ratio for the tabulated inlet-air pressures. It is emphasized that whereas, for a constant inlet-air temperature, curves varying only in the proportionality constant can be drawn which are applicable to any fuel, for a variable inlet-air temperature each set of data applies to only one fuel.

Without the intercooler between the supercharger and the cylinders, the indicated mean effective pressure is no longer proportional to the inlet-air pressure P_1 because of the heating that has taken place within the supercharger. Instead, the indicated mean effective pressure for a constant inlet-air temperature and pressure to the supercharger is proportional to the supercharger compression ratio R_s and, as before, to the cycle efficiency as expressed by the relationship:

$$\text{i. m. e. p.} \propto R_s \times E_c \tag{10}$$

The values of R_s are obtained from the second column in table IX, and the values of E_c from the compression ratios listed in column 5 and the corresponding values of E_c obtained from the tabulated cycle efficiencies already given. The indicated mean effective pressure factors are given in column 7 and are again a proportionality factor.

TABLE IX

ESTIMATION OF MAXIMUM PERMISSIBLE I. M. E. P. FACTOR FOR ISO-OCTANE FROM FUEL-RATING CURVE IN FIGURE 4

[Inlet-air temperature, 120° F.; audible knock; flat-disk combustion chamber; no intercooler]

1	2	3	4	5	6	7	8
Inlet-air pressure, P_1 (in. Hg abs.)	Supercharger compression ratio, R_s	T_1 (°F. abs.)	RP_1/T_1 (fig. 4)	Engine compression ratio, R	E_c	$R_s \times E_c$	(7)× 0.273/0.480
30	1.00	580	0.455	8.80	0.480	0.480	0.273
34	1.09	601	.435	7.70	.466	.504	.287
38	1.18	619	.415	6.77	.436	.514	.292
42	1.27	640	.392	5.97	.413	.524	.298
46	1.35	658	.370	5.29	.392	.530	.301
50	1.44	672	.355	4.78	.372	.536	.305
54	1.52	687	.340	4.33	.355	.540	.307
58	1.60	700	.325	3.92	.338	.540	.307

These values can be compared with those presented in figure 19 for the condition of constant inlet-air temperature by using a corresponding set of conditions, that is, the condition of no boost. In the second series of data, the compression ratio for no boost is 8.80, and the indicated mean effective pressure factor is 0.480.

For the condition of constant inlet-air temperature, the indicated mean effective pressure factor at a compression ratio of 8.80 is 0.273. Consequently, in order to compare the values from the foregoing proportionality factor with the indicated mean effective pressure factors for constant inlet-air temperature, the term $R_s \times E_c$ must be multiplied by 0.273/0.480 as given in column 8.

In figure 20 is shown the effect of compression ratio on the maximum permissible indicated mean effective

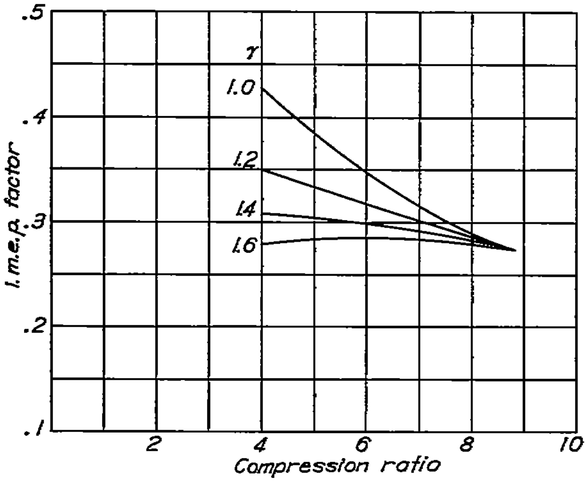

FIGURE 20.—Effect of various degrees of intercooling between supercharger and engine cylinders on maximum permissible i. m. e. p. factor. Iso-octane; audible knock.

pressure factor for various degrees of intercooling between the supercharger and the engine cylinders. The compression exponent indicated for each curve expresses the degree of intercooling. For an exponent of $\gamma=1.0$, the curve is the same as that shown in figure 19, in which it was assumed that the air entered the engine at a constant temperature, 120° F. The curves for the exponents of 1.2 and 1.6 were obtained in the manner illustrated for the value of 1.4. The curves emphasize the gain in maximum power that can be obtained by installing an intercooler so that the air or charge enters the cylinders at a temperature close to or equal to that at which it enters the supercharger. With an exponent of 1.6, the maximum permissible indicated mean effective pressure factor reaches a maximum at a compression ratio of 6.3. Dicksee (reference 18) pointed out in 1927 that, for any one fuel, one certain compression ratio would give the maximum permissible power provided that the air or charge not be cooled after it left the supercharger.

In the subsequent calculations presented in this report, it will be assumed that the value of γ is 1.4 for the condition of no intercooling or partial intercooling between the supercharger and the engine cylinders.

MAXIMUM PERMISSIBLE ENGINE PERFORMANCE WITH DIFFERENT FUELS

In figure 21 are compared the maximum permissible indicated mean effective pressure factors for three fuels with no intercooler between the supercharger and the cylinders. The corresponding inlet-air pressures are given in figure 22. The right-hand end of the indicated

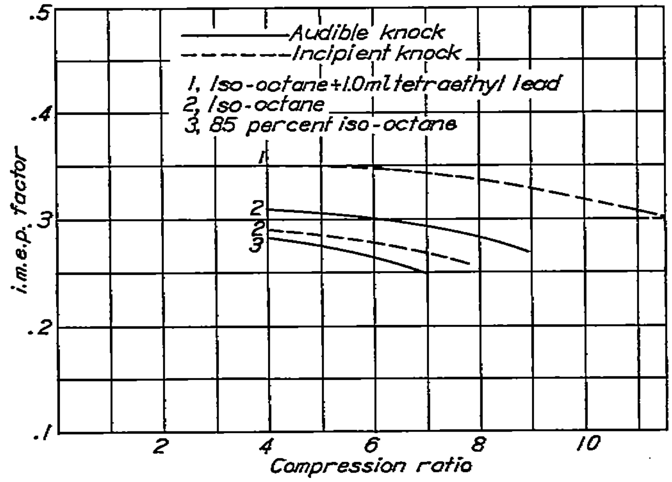

FIGURE 21.—Comparison of maximum permissible i. m. e. p. factors at different compression ratios for three different fuels. No intercooler (γ, 1.4) between supercharger and engine cylinders.

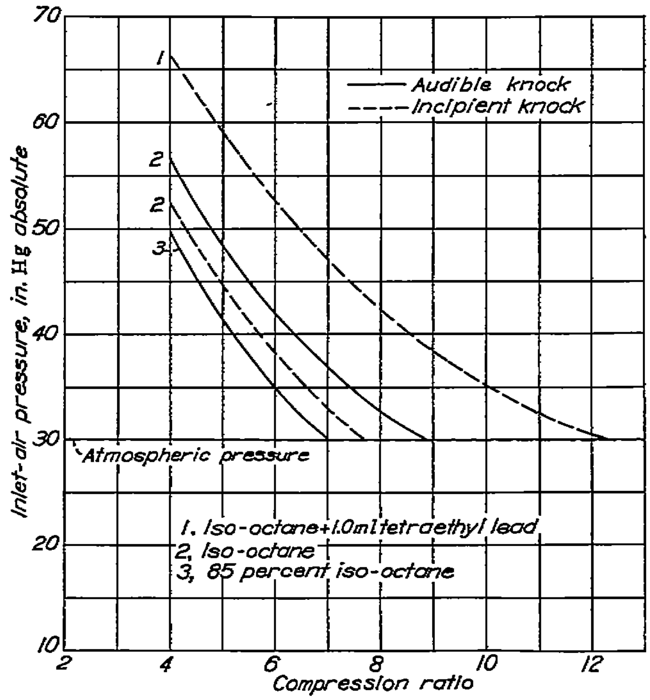

FIGURE 22.—Comparison of maximum permissible inlet-air pressures at different compression ratios for three different fuels. No intercooler (γ, 1.4) between supercharger and engine cylinders.

mean effective pressure curves represents in each case the condition of 120° F. inlet-air temperature and 30 inches of mercury inlet-air pressure. As the compression ratio is decreased, the curves tend to approach each other in the same manner that the rating curves of the fuels approached each other as the temperature of the inlet air was increased (fig. 4).

If it is assumed that a maximum boost pressure of 10 inches of mercury can be obtained, the maximum performances possible with the three fuels are shown in the following table:

Fuel	Compression ratio	I. m. e. p. factor	Specific fuel consumption factor	Knock
1	8.5	0.34	0.29	Incipient.
2	6.3	.30	.33	Audible.
3	5.2	.27	.36	Do.

Fuel 1 therefore represents a gain of 25 percent in maximum indicated mean effective pressure over fuel 3 and a decrease of 22 percent in the specific fuel consumption. With fuel 1, the peak pressures for this performance would be 1.5 to 2 times those with fuel 3.

CORRELATION OF RATING CURVES OBTAINED ON DIFFERENT ENGINES

As was shown in table II, it is possible to get two different rating curves for one fuel on the same engine by eliminating hot spots. This variation should be attributed to the engine. The data in reference 6 showed a greater temperature effect from variations in compression ratio than is shown by the N. A. C. A. data presented herein and by the data presented in references 3 and 5. The general trends shown in the previous figures should nevertheless be applicable to different engines.

The data obtained at the N. A. C. A. laboratories on the flat-disk and the pent-roof combustion chambers installed on the 5- by 5¾-inch engine permit a correlation to be made between the data for the two forms of combustion chamber.

The rating curve for iso-octane at incipient knock in the pent-roof combustion chamber determined from the data in table III is shown in figure 23, together

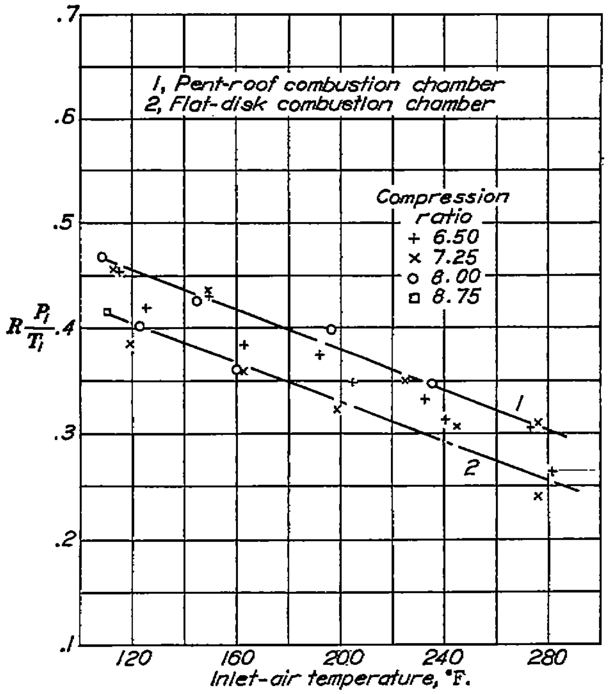

FIGURE 23.—Comparison of rating curve for iso-octane with two different combustion chambers. Incipient knock.

with the curve for the flat-disk combustion chamber. The curves are approximately parallel, but that for the flat-disk combustion chamber is 0.050 RP_1/T_1 lower than that for the pent-roof combustion chamber. In table X are given the necessary computations to determine the estimated indicated mean effective pressure curves from the two rating curves for the conditions listed.

Column 7 of table X contains the indicated mean effective pressure factors for the two combustion chambers using the same fuel. In column 8 the indicated mean effective pressure factors for the flat-disk combustion chamber have been multiplied by 0.273÷0.480 so that the factors can be directly compared with those previously given. These values have already been plotted in figure 21. The performance factors for the fuels, and not for the engines, can be compared by finding a factor by which to multiply the values in column 7 to correlate the values with those for the flat-disk combustion chamber. At any one compression ratio, the two heads should show the same factor for the one fuel. The disk combustion chamber has a factor of 0.262 at a compression ratio of 7.70. The compression-ratio column for the pent-roof combustion chamber shows a compression ratio of 7.69 with a factor of 0.502. Because these two values of compression ratio are practically the same, the values in column 7 for the pent-roof combustion chamber are multiplied by 0.262/0.502. The resulting indicated mean effective pressure factors are given in column 8. The factors for the two combustion chambers are plotted in figure 24. The data show that a single curve represents both combustion chambers (curve 2).

TABLE X

ESTIMATION OF MAXIMUM PERMISSIBLE I. M. E. P. FACTOR FOR TWO DIFFERENT COMBUSTION CHAMBERS USING THE SAME FUEL

[Fuel, iso-octane; knock, incipient; inlet-air temperature to supercharger, 120° F.; no intercooler]

1	2	3	4	5	6	7	8
P_1 (in. Hg abs.)	R_s	T_1 (°F. abs.)	RP_1/T_1	R	E_c	E_sR_s	(7) F
Flat-disk combustion chamber, 2,500 r. p. m.							
							F=0.273/0.480
30	1.00	580	0.405	7.70	0.460	0.460	0.262
34	1.09	601	.386	6.82	.478	.478	.272
38	1.18	619	.370	6.03	.489	.489	.278
42	1.27	640	.350	5.34	.499	.499	.284
46	1.36	658	.332	4.75	.502	.502	.286
50	1.44	672	.320	4.38	.507	.507	.288
54	1.52	687	.305	3.88	.509	.509	.289
Pent-roof combustion chamber, 2,200 r. p. m.							
							F=0.262/0.502
30	1.00	580	0.455	8.80	0.480	0.480	0.253
34	1.09	601	.435	7.69	.461	.502	.262
38	1.18	619	.418	6.81	.438	.517	.270
42	1.27	640	.398	6.07	.416	.528	.276
46	1.36	658	.381	5.45	.396	.538	.281
50	1.44	672	.367	4.93	.378	.544	.284
54	1.52	687	.353	4.49	.362	.550	.287
58	1.60	700	.340	4.11	.348	.557	.289

The curves presented in figure 24 do not indicate which form of combustion chamber permits the highest indicated mean effective pressure. Small changes in design, such as the elimination of the recesses in the piston used with the pent-roof chamber, might change the relationship of the curves in figure 23. The figures indicate that this method of estimating maximum permissible performance permits a certain degree of correlation between different combustion-chamber forms, but that certain differences are dependent on the design.

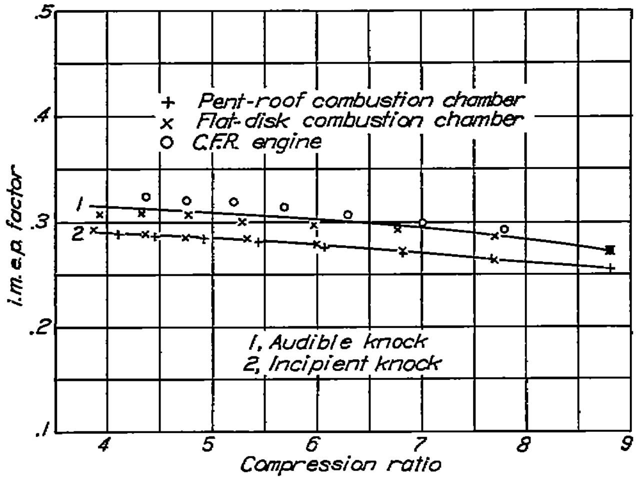

FIGURE 24.—Effect of compression ratio on maximum permissible i. m. e. p. factor for iso-octane for two different combustion chambers. No intercooler between supercharger and engine cylinders.

Curve 1 in figure 24 shows the correlated data for the flat-disk combustion chamber with iso-octane and the data obtained by Heron and Gillig from a C. F. R. engine using C. F. R. S–1 fuel (unpublished data). The S–1 fuel is practically identical with the fuel listed as iso-octane in the N. A. C. A. tests. Heron and Gillig found that, at a speed of 1,800 r. p. m. and a coolant temperature of 350° F., the C. F. R. S–1 reference fuel permitted an inlet-air pressure of 49.7 inches of mercury at an inlet-mixture temperature of 110° F. and an inlet-air pressure of 48.2 inches of mercury at an inlet-mixture temperature of 212° F. The correlation between the C. F. R. engine and the N. A. C. A. 5- by 5¾-inch engine shows more variation than that for the two combustion chambers on the N. A. C. A. engine. Even so, the variation is only ±3 percent. Although more test data are needed, the curves indicate that satisfactory correlation between different engines can be obtained provided that the performance is limited by knock.

Correlation between two fuels used in two different types of combustion chamber can be obtained from tables II and IV. By the method used to obtain the previous figures, it can be shown that, for the pent-roof combustion chamber, the indicated mean effective pressure factors for the iso-octane, when multiplied by 0.500, lie on the same curve as the data for the flat-disk combustion chamber (fig. 25). In the correlation of data for more than one fuel, the same factor should be used for all fuels. The use of this same factor gives the curve indicated for the pent-roof combustion chamber with the iso-octane plus 1.0 ml of tetraethyl lead. The curve lies below the corresponding curve for the flat-disk chamber. The data show that the flat-disk combustion chamber permitted a greater percentage increase in performance than did the pent-roof chamber when 1.0 ml of tetraethyl lead was added to the iso-octane. It is concluded from the curves that no method of fuel rating on a single engine will give results which are accurately applicable to all engines but that it is possible to make an estimation of the approximate gain permitted by the use of improved fuels which will indicate basic differences in the behavior of different engines with these fuels. It is emphasized that these curves do not show which combustion chamber gave the highest engine output but indicate only the proportional increases permitted by the two fuels.

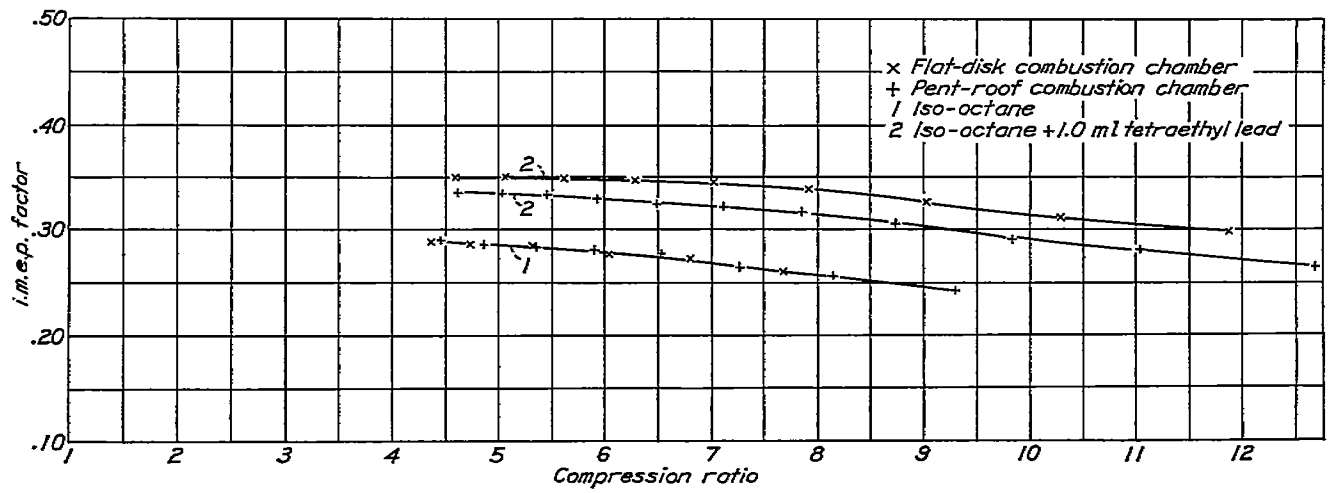

FIGURE 25.—Correlation of maximum permissible i. m. e. p. factors for two fuels in two combustion chambers of different design. No intercooler between supercharger (γ, 1.4) and engine cylinders; incipient knock; engine speed, 2,500 r. p. m.

MAXIMUM PERMISSIBLE ENGINE PERFORMANCE

In the figures presented, it has been assumed that the engine is operated at a constant compression ratio. The data show that, in order to obtain maximum power for take-off and minimum fuel consumption for cruising, the engine should be operated at a variable compression ratio. The variation of the actual compression ratio of an engine leads to considerable mechanical complication. The effective compression ratio can be varied, as shown in figures 16 and 17, by changing the spark advance.

The most important fact to be learned from figures 16 and 17 is that, by retarding the spark, the maximum permissible boost pressure can be considerably increased. Consequently, for the most efficient use of any fuel, the compression ratio should be the highest value permissible for the desired power output, and the inlet-air temperature should be the lowest compatible with the volatility and freezing characteristics of the fuel. This condition represents the lowest specific fuel consumption, and it has been shown that, with iso-octane plus 1.0 ml of tetraethyl lead, the compression ratio at atmosphereic inlet pressure is about 12. For maximum power in take-off, the spark can be retarded and the inlet-air pressure can be increased. If no or partial intercooling is provided, the optimum performance of the engine is represented by the data given in figures 20 and 21. With a degree of intercooling represented by $\gamma=1.4$ and with iso-octane plus 1.0 ml of tetraethyl lead, the permissible power can be increased 19 percent by retarding the spark until the effective compression ratio is reduced from 10 to 6.

Figure 19 shows that, with intercooling, the same decrease in effective compression ratio permits the maximum permissible power to be increased 38 percent. In neither of these cases has any change in speed been considered. The compression ratio of 10 results in a decrease of 17 percent in the specific fuel consumption factor from the consumption at a compression ratio of 6.

The amount the spark can be retarded at high compression ratios will probably be limited by preignition because, although the end-gas temperature and density can be maintained constant, the density and the temperature preceding ignition is increased at the late spark advances.

Although these values may be overoptimistic, it is probable that, by the use of a high-compression-ratio engine and a retarded spark for take-off conditions, compression ratios higher than those used at present can be employed for cruising conditions and that the use of these compression ratios will result in a saving in fuel consumption. There seems to be no reason to believe that fuel consumptions of 0.35 pound per brake horsepower-hour should not be obtained with iso-octane fuel plus 1.0 ml or more of tetraethyl lead per gallon by operating the engine at a compression ratio of about 10 for cruising, by retarding the spark to a lower compression ratio, and by boosting to provide sufficient power for take-off, provided that an intercooler for the incoming mixture can be provided.

Taylor, Ku, and Kennedy (reference 19) ran similar tests simulating altitude conditions and suggested varying the spark advance as an effective method of maintaining critical altitude power down to sea level.

Additional data on the foregoing method of engine operation are shown in table XI. In this test the engine was operated at the optimum spark advance at a compression ratio of 6.5 and the maximum permissible inlet-air pressure was determined for an inlet temperature of 200° F. The compression ratio was then increased to 8.0 and the spark retarded until the engine could be operated at this same inlet-air pressure and temperature. The results show that engine data were nearly the same for both conditions of operation except that the exhaust temperatures were slightly lower at the higher compression ratio. When the spark advance was set for the optimum value at the higher compression ratio, the maximum permissible indicated mean effective pressure was decreased to 173 pounds per square inch but the specific fuel consumption was decreased to 0.445 pound per indicated horsepower hour.

TABLE XI

EFFECT OF SPARK ADVANCE ON MAXIMUM PERMISSIBLE INLET-AIR PRESSURE AT TWO COMPRESSION RATIOS

[Engine speed, 2,500 r. p. m.; fuel, iso-octane+1.0 ml of tetraethyl lead per gallon; inlet-air pressure, maximum without knocking; air-fuel ratio, 12.5 (maximum power); inlet-air temperature, 200° F.]

	Compression ratio		
	6.50	8.00	8.00
Optimum spark advance, deg	31	29	29
Inlet-air pressure, in. Hg	45	45	37
Spark advance, deg	31	20	29
I. m. e. p., lb. per sq. in	210	214	173
I. f. c., lb. per i. hp.-hr	0.513	0.498	0.445
Exhaust temperature, °F	1,430	1,400	----------
Temperature rise, °F	11	10	----------
Maximum cylinder pressure, lb. per sq. in	925–750	825–750	----------

III—COMPARISON OF KNOCKING-CHARACTERISTIC CURVES WITH OCTANE NUMBER

The most generally accepted index of fuel rating is octane number. This index depends on a comparison of the knocking characteristics of a given fuel with a blend of heptane and iso-octane. Since the knocking characteristics of different fuels do not necessarily have the same relative values for different engine operating conditions, the octane number of a fuel will vary with engine operating conditions unless the characteristics of the fuel are similar to heptane and iso-octane blends, as has been pointed out by Heron and Beatty (reference 20). The purpose of octane number is not to indicate the maximum permissible performance that can be obtained from a fuel under any operating conditions but to indicate whether the fuel will knock under the most severe conditions to which it will be subjected. In general, this most severe condition will be either at take-off when the power output of the engine is high but knock is suppressed by enriching the mixture or at cruising when the power output is low but the mixture has been leaned to the minimum permissible value. If the fuels to be rated have similar characteristics, a single value of octane number representing one of these two conditions will probably be satisfactory. If fuels of different characteristics are to be rated, it may be necessary to determine octane numbers at these two most severe conditions.

The method of considering the fuels and the engines presented in the present report is suggested as a means of determining the relative maximum permissible engine performance that can be obtained under any operating conditions. It presents a method of determining the manner in which the combination of engine and fuel can be used most efficiently. Although these two methods of fuel rating serve different purposes, they should be compared.

In figures 26 and 27, the maximum permissible density factors are plotted against ASTM octane numbers for the blends used in the N. A. C. A. tests and for the blends used by Heron and Gillig in the tests reported in reference 9. In each case for the

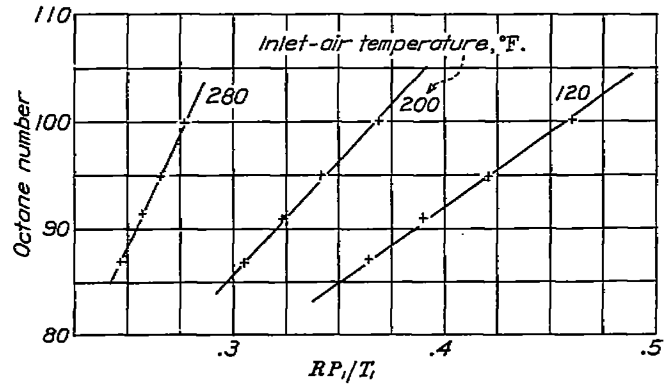

FIGURE 26.—Relationship between maximum permissible density factor and octane number for fuel blends used in N. A. C. A. tests.

N. A. C. A. data, the curves are straight lines (fig. 26). The slopes of the lines vary and, as a result, the actual variation in engine performance is not a constant with respect to octane number. At the lowest inlet-air temperature tested, 10 octane numbers represent a change in the maximum permissible density factor of 0.070; and, at the highest inlet-air temperature, the same range represents a change of 0.023. If a constant compression ratio is assumed, the increase in the maximum permissible density factor represents a proportional increase in maximum permissible indicated mean effective pressure.

The data of reference 9 (fig. 27) extend over a greater range of octane number than those of the N. A. C. A. tests and show that the curves at different engine speeds have different slopes and also that, for a series of blends at constant engine speed and jacket temperature, the slope of the curve changes. With the data presented in figure 27, each curve apparently consists of two straight lines. These curves emphasize the fact brought out in various other papers that, as the octane number is increased, the corresponding improvement in maximum permissible engine output becomes greater for a constant increment of octane number.

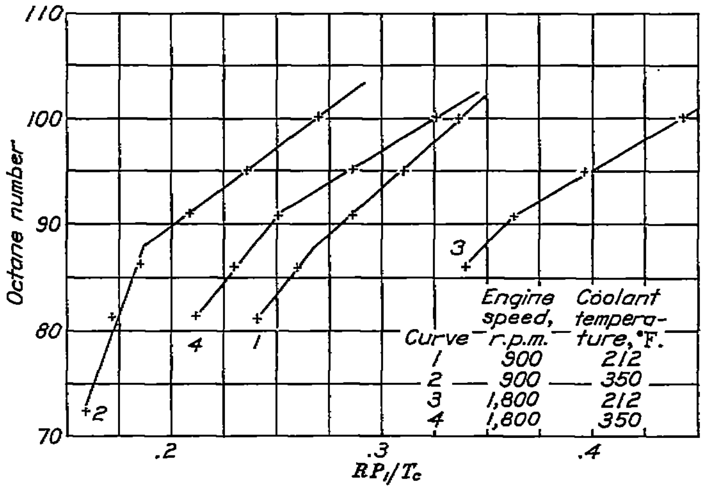

FIGURE 27.—Relationship between maximum permissible density factor and octane number for blends of S-1 and M-1 reference fuels (data from reference 9).

CONCLUSIONS

The results presented in this report show that, by a determination of the knocking characteristics of a fuel in an engine as a function of the highest permissible inlet-air density at any inlet-air temperature, data obtained at one compression ratio or at one inlet-air pressure are applicable to a series of inlet-air pressures and compression ratios at the different inlet-air temperatures tested.

Analysis of the more important engine factors affecting knock leads to the conclusion that the most important independent variables in any one engine are the inlet-mixture density and temperature and the mixture ratio.

The data show that preignition must be treated separately from knock if the fuels are to be adequately rated in the engine. In the case of knock, the maximum permissible performance increases with speed for a constant spark advance; whereas, with preignition, the indication is that the maximum permissible performance decreases with engine speed.

The analysis shows that for any particular fuel the maximum permissible power increases as the compression ratio is decreased provided that the inlet-air temperature is kept constant and the performance is limited by knock and not by preignition. For the cases in which the inlet air is heated an increasing amount as the boost pressure is increased, the rate of maximum permissible power increase with decreasing compression ratio decreases and finally passes through a value of zero as the exponent of adiabatic compression within the supercharger is increased. For the particular example cited in this report, an exponent of 1.6 resulted in an increase in the maximum permissible power as the compression ratio of the engine was decreased until the ratio reached a value of 6.3. Further decrease in the compression ratio caused a decrease in the maximum permissible power output.

The data show that a certain amount of correlation can be obtained between the knocking-characteristic curves of several fuels obtained on different engines but that there are certain differences which are caused by the variation in engine designs.

Presentation of the data on the basis of maximum permissible inlet-air density shows that the octane scale has a value in relation to engine output that varies with both octane number and the conditions of engine operation.

LANGLEY MEMORIAL AERONAUTICAL LABORATORY,
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., *September 14, 1938.*

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